GREENHOUSE GAS REDUCTION STRATEGY FOR HAWAI'I

Phase II: Forecasts and Mitigation Options for Non-Energy Emission Sources

Final Report to

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List of Acronyms

Abbreviation	Full Name
AG-1	Agricultural Zone 1 (O'ahu)
AG-2	Agricultural Zone 2 (O'ahu)
BTU	British thermal unit (= energy required to raise one pound of water one degree F)
C	Carbon, Centigrade
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DAGS	Hawai'i State Department of Accounting and General Services
DBEDT	Hawai'i State Department of Business, Economic Development and Tourism
DLNR	Hawai'i State Department of Land and Natural Resources
DM	German mark
DOH	Hawai'i State Department of Health
DPED	Hawai'i State Department of Planning and Economic Development (now DBEDT)
ECU	European Currency Unit
EPA	United States Environmental Protection Agency
F	Fahrenheit
FF	French franc
GWP	Global warming potential
H_2	Hydrogen gas
H_2S	Hydrogen sulfide
HITECH	Hawai'i Integrated Technology Biogas Facility
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
KNO_3	Potassium nitrate
kW	Kilowatt
kWh	Kilowatt-hour
lb	Pound
m^2	Square meters
Mcal	Megacalories (= 1 million calories)
ME	Metabolizable energy
MSW	Municipal solid waste
MW	Megawatt
N_2	Nitrogen gas
N_2O	Nitrous oxide
NH_4	Ammonia
NO_X	Nitrogen oxides

List of Acronyms (cont.)

OTA	US Congress Office of Technology Assessment
OTEC	Ocean thermal energy conversion
pH	Negative log of hydrogen ion activity
PICHTR	Pacific International Center for High Technology Research
RDF	Refuse-derived fuel
t	Tons
TCE	Tons of carbon equivalent
US	United States
WIP	Waste in place
yd^3	Cubic yards
yr	Year

Executive Summary: An Action Plan Proposal for Hawai'i

Hawai'i occupies a unique position with regard to global climate change. The Hawaiian Islands lie in the semitropical zone, enabling them to utilize information and technology designed for both tropical and temperate zones. At the same time, the success stories in Hawai'i can also be used in both of these neighboring zones. Furthermore, Hawai'i combines a modern economy with a progressive and informed government which has led the way internationally in several arenas regarding environmental protection. The topics of this report comprise the non-energy sectors and their greenhouse gas emissions. It begins with an Action Plan, which serves as an executive summary. A review of the inventory of greenhouse gas emissions for the state follows. Third, a set of graphs predict the trends in CO_2, CH_4 and N_2O emissions for the state, both with and without the measures recommended in the Action Plan. Finally, the bulk of the document discusses the recommendations of the Action Plan in detail, providing information on what is happening in Hawai'i in each sector, and details of the recommended measures or technologies. This document should serve to spur discussion of ways in which Hawai'i can continue to provide an example of conscientious leadership in innovative environmental protection measures.

This report seeks to construct a semi-quantitative prioritization of recommendations for reducing Hawai'i's non-energy greenhouse gas emissions. The major options below are prioritized, within each non-energy sector and, in some cases, between sectors. Each of these options has potential in and of itself, but an Action Plan that integrates the individual components would facilitate support for each, and would result in greater benefits due to the synergy and feedback between the various options. It is imperative to note that this Action Plan requires a joint effort between the public and private sectors in order to be truly effective. Multiparty task forces are one example of such joint efforts.

Recommended major options are shown in the order of priority. The following summary of the findings of the study and the predicted emissions, based on these options, are illustrated in Figures 2-9. Where no prioritization is considered possible or productive, for example in programs where several projects must coexist and interact in order to make any one of them productive, options are merely listed without assigning a priority value.

A. <u>Source Reduction, Recycling and Landfills</u> (p. 17)

1. Pre-Consumer Source Reduction (low cost, high benefit).
   - *e.* *Establish and implement a "green packaging" label.*
   - *b.-c.* *Increase efforts of government agencies to (a) buy in bulk, (b) purchase packaging which uses recycled materials, and (c) use two-sided copiers.*
   - *a.* *Educate local commodity producers and importers regarding the desirability of reducing packaging volume for commodities.*

2. Post-Consumer Source Reduction (low to moderate short-term cost, high benefit).

   b. Provide incentives for private recycling operations to become established.

      ii. Investigate increasing tipping fees at landfills.

      iii. Continue and expand such joint public-private efforts as the Partnership for the Environment.

      v. Encourage government commitment to procure locally-recycled materials.

      vi. Provide tax breaks and low -interest loans to recyclers.

   a. Support county recycling programs and improve coordination efforts and internal programs of state government offices.

   Although the higher wages paid to government workers could more than offset the benefits accrued by internalizing all portions of the commodity-waste cycle, this is still a key component of the state's recycling efforts

3. Construct and Operate Waste-to-Energy Plants (moderate to high short-term cost, moderate benefit).
   Carefully evaluate the pros and cons of constructing RDF-type and high-temperature volatilization plants on the neighbor islands.

4. Reduce Methane Emissions from Landfills (moderate cost, moderate to high benefit).
   Support (via loans, tax breaks and/or direct subsidies) methane collection at landfills closed within the last 20 years or scheduled to be closed soon.

   b. Install or promote installation of equipment at large landfills (>1.1 million tons Waste-In-Place (WIP) to (a) pipe unrefined gas to neighboring operations for energy and/or heat, (b) burn unrefined gas for energy onsite, or (c) refine and pipe natural gas to higher-end users or utilities. Provide educational seminars and reports to inform landfill operators or new technology for gas collections.

   a. Install equipment to vent and flare methane systems at medium landfills (0.5-1.1 million tons WIP)

   c. Promulgate laws reducing methane emissions from landfills which are more stringent than federal laws.

   d. Avoid deprivatizing landfills.

B. <u>Livestock and Manure Management</u> (p. 46)

1. Recover Methane from Stored Manure (moderate to high cost, moderate benefit).

    a. For the largest farms, evaluate pros and cons of a system which would combine anaerobic digestion, burning of the methane for power and photosynthetic reclamation of the remainder.

    c. Provide incentives for transfer of waste slurries to centralized waste-to-energy plants, especially ones which also process green waste and food waste.

    b. Evaluate and support placement of covers on liquid waste lagoons at relatively large farms support treatment of solid manure with plug flow or mixed tank digesters and subsequent flaring or use of methane.

2. Improve the Diet Quality of Ruminants (low to moderate cost, moderate benefit).

    a. Promote and support research into economically viable diets for dairy cattle and pasture supplements for beef cattle which increase productivity without increasing methane emission rates, emphasizing maximization of nitrogen-fixing crops where possible.

    b. Educate markets and consumers regarding the combined health benefits and reduced methane produced by low-fat cattle products.

3. Improve Efficiency of Livestock Feed Application (low cost, low to moderate benefit).

    a. Improve monitoring and design of feed bins.

    b. Maintain a good parasite control program.

4. Increase Aerobic Treatment of Manure (low cost, moderate benefit).

    a. Expand the market for composted manure as fertilizer.

        i. <u>Provide expertise and financial incentives to swine and poultry owners who wish to compost and market their manures, targeting systems which mix the manure with green waste.</u>

        ii. <u>Identify and work to eliminate any significant bottlenecks to the integration of livestock and crop production operations.</u>

        iii. <u>Reduce the permitting process for farms which desire to transport composted material to offsite customers.</u>

b. *Direct land application for aerobic decomposition.*

ii. Promote storage of manure in closed tanks or pits, as opposed to either (a) open pits or (b) anaerobic digestion (unless the methane generated by the digester is captured and flared or utilized).

i. Evaluate financial incentives promoting purchase of equipment for injecting animal slurry into soil as a crop amendment.

C. Fertilizer and Compost (p. 65)

1. Promote Epanded Use of Organic Fertilizers (low to moderate cost, moderate to high benefit).

a. *Initiate and support diversion of more green waste to municipal, county, and private composting and mulching factories.*

i. Concentrate on aerobic and dry anaerobic methods.

ii. Advertise and educate the public regarding existing programs, especially for home pick-up of separated green waste.

iii. Improve efforts to compost or mulch green waste.

b. *Help expand the market for composted manure as fertilizer.*

c. *Help expand production and marketing of anaerobically digested biosolids (sewage sludge) as fertilizer.*

2. Improve the Efficiency of Fertilizer Use (low to moderate cost, moderate benefit).

a. *Management approaches.*

i. Promote improved fertilizer application rates and timing.

ii. Promote improved frequency of soil testing.

iii. Promote improved placement of fertilizer.

iv. Promote reduced crop rotations.

b. *Technology approaches.*

i. Encourage reduced use of fertilizers containing anhydrous ammonia.

ii. Encourage increased use of fertilizers with slow-release coatings.

iii. Promote increased application of nitrification inhibitors to fertilizer.

iv. Promote increased application of hormones to grasses of recreational areas such as golf courses and sports fields.

v. Promote planting of grasses and crops which require less fertilization.

3. Promote Planting of Cover Crops which Capture Nitrogen (low to moderate cost, low to moderate benefit). See recommendation below on agroforestry.

4. Promote Improved Soil Management (low to moderate cost, low benefit).

a. *Promote and undertake afforestation and removal of marginal lands from agricultural production.*

b. *Study and promote reduction of crop tillage intensity.*

5. Indirect Measures (low cost, indeterminate benefit).

a. *Keep and compile better records of agriculture practices.*

b. *Modify land tenure to allow longer-term leases, thus giving better encouragement to farmers to spend money on long-term conservation and emissions reduction practices.*

c. *Develop a policy to manage and possibly regulate fertilizer use statewide.*

D. Land Use Management (p. 79)

1. Establish Tree Plantations (low cost, high benefit).

b. *Encourage conversion of abandoned agricultural land to tree plantations.* Continue to support DLNR's Forest Stewardship program, which maintains partnerships with private landowners regarding tree planting on agricultural land.

c. *Landowners with forested lands should be provided tax incentives, even when such forests are not predominantly native.*

a.. *Increase the productivity of existing plantations. Support planting of genetically-improved trees.*

2. Promote Agroforestry (low cost, moderate to high benefit).

   a. *Promote the planting of nitrogen-fixing trees along with crops to act as windbreaks, fertilizer supplements, and eventually sources of bioenergy or lumber.*

3. Promote Urban Tree Planting (low cost, low to moderate benefit).

   a. *Undertake (or expand) community-wide programs for shade tree planting.*

   b. *Promote energy conservation activities by providing information on landscaping designs.*

   c. *Provide information to--and incentives for--developers to build well-landscaped buildings and communities.*

4. Improve Forest Management (low to moderate cost, low to moderate benefit).

   b. *Continue to support the governor's initiative calling for a comprehensive examination of Hawai'i's forests, expanding the focus to include greenhouse gas sequestration.*

   c. *Land destined for conversion to non-forest uses, and any land for which the final use is uncertain, should be kept as managed forest indefinitely or until the need for clearing arises.*

   a. *Increase productivity of managed forests.*

E. **<u>Crop Burning and Bioenergy Crops</u>** (p. 87)

1. Study and Encourage Planting of Crops (aside from those in #4 below). Which do not require burning as do sugar cane and pineapple residue (moderate to high benefit).

2. Promote Biomass-to-Energy Plants, Especially those Utilizing Crops Grown Expressly for that Purpose (high benefit).

3. Study and Promote Bioenergy Plantations (low to moderate benefit).

   a. *Encourage planting of sugarcane cultivars, napiergrass and other fast-growing biomass crops.*

   b. *Encourage agronomic practices which maximize biomass.*

4. Study and Promote Plowing Crop Waste Under Rather Than Burning It (low cost, low to moderate benefit).

F. Municipal Sewage Management (p. 92)

1. Use Recovered Methane at Sewage Treatment Plants (moderate cost, moderate benefit).

2. For Non-Vegetable Crops, Directly Apply Dried Sewage Sludge as Fertilizer and Use Sewage Effluent for Nutrient-Rich Irrigation (moderate cost, moderate benefit).

3. Compost Sewage Sludge for Use on Vegetables and Other Crops and Pastures (moderate cost, moderate benefit).

4. Study Efficacy of Injecting CO_2 and Possibly Methane Into Sewage Effluent Being Sent Into Offshore Outfall Pipes (moderate to high cost, moderate to high benefit).

5. Consider the Use of Sewage Effluent as Reinjection Fluid for Geothermal Wells in the Puna District of the Big Island (high cost, low benefit).

G. Intersectorial Measures (p. 100)

1. Provide Certain Areas with Titles Designating their Sensitivity to Agents which Contribute to Greenhouse Gas Emissions (low cost, moderate benefit).

   a. Designate certain bays, such as Kane'ohe Bay, Mamala Bay and Hilo Bay as Nutrient-Sensitive Areas, in the same manner as Chesapeake Bay (IPCC, 1991, p. 114).

   b. Designate certain agricultural areas and/or watersheds as soil conservation areas, where the relevant measures discussed in this document are particularly stressed.

2. Establish a Statewide Greenhouse Gas Reduction Program With Specific Goals and a Full-Time Staff Tasked With Implementation, Monitoring and Public Education (moderate cost, moderate benefit).

3. Create a Database Regarding Activities Which Affect Greenhouse Gas Emissions (moderate cost, moderate benefit).

This Executive Summary: Action Plan presents a comprehensive overview of the measures which are likely to have positive impacts on greenhouse gas reduction efforts. Where possible, they balance effectiveness and costs, prioritizing those measures which maximize the former and minimize the latter.

I. INTRODUCTION

Most scientists agree that human-induced climate change is currently underway. This conclusion is supported by a steady rise in global temperatures over the last century, the retreat of many glaciers, shifts in the timing of seasons, and the poleward migration of the ranges of many plant and animal species (Flavin and Tunali, 1996, p. 5 and 13). In 1995, the Intergovernmental Panel on Climate Change (IPCC) projected a rise of 1.0 to 3.5 degrees Celsius (1.8 to 6.3 degrees Fahrenheit) between 1990 and 2100, and a consequent sea level rise of between 15 and 95 centimeters. Even at the lower end of these projections, the global climate will change faster in the next few decades than at any time since civilization began, as carbon dioxide (CO_2) concentrations reach levels which the planet has not seen for hundreds of thousands of years (Flavin and Tunali, 1996, p. 17-18 and 28).

However, considerable uncertainty prevails over the specific consequences of global warming, as well as the best mix of policies which would allow us to stop or reverse this unintended planet-wide experiment. The very scope of climate change--in terms of both its geographic breadth and its multigenerational time frame--challenges societies to work individually and cooperatively to correct potential problems before they occur or become inevitable. The best estimates available suggest that regions with relatively high rainfall, including most of the Hawaiian Islands, will become wetter and stormier as well as warmer. This, combined with a rise in sea level, would increase damage to coastal areas and places subject to flooding and landslides. Warming itself not only increases energy use (through increased air conditioning, for example), but also may affect growth and diversity of coral reefs that protect the coastal areas of the state. Higher temperatures could also increase the range of disease-carrying vectors, affecting both Hawai'i's people and its native flora and fauna. Furthermore, damage to places far from Hawai'i can also affect these islands through decreasing tourism and increasing prices for food and goods (Watkins, 1991, throughout; Flavin and Tunali, 1996, p. 21-27).

In recognition of this potential threat to the environmental and economic well being of the country, President Clinton launched the Climate Change Action Plan in 1993. This plan includes 50 measures intended to promote energy efficiency, commercialize renewable energy technologies, and encourage tree planting in the US. Two-thirds of these measures are voluntary. The goal of this plan is to hold carbon dioxide emissions to within 3% of the 1990 level by 2000. However, a 1996 projection by the US Department of Energy indicates that without new policy initiatives, by the year 2000, America's carbon emissions will exceed 1990 levels by a full 11%. This gap stems both from weaknesses in the original plan and from funding cuts made by Congress in 1995 (Flavin and Tunali, 1996, p. 35-36). In light of these problems, and in order to achieve the nation's goals for reduction of greenhouse gas emissions, action and cooperation will be necessary at the state, county and municipal levels as well as at the federal level.

Over the last decade or so, the state and county governments of Hawai'i have begun implementing measures specifically aimed at decreasing air pollution, including reductions of some greenhouse gases. Yet none of these measures specifically seek to reduce Hawai'i's contribution to global warming. Nor, up until now, has there been any central action plan regarding responses to the potential negative effects of these emissions.

The aim of the present study, has been to develop an inventory of the non-energy sources of greenhouse gases in Hawai'i (Phase I) and then using that data, to forecast trends of non-energy emissions from Hawai'i to the year 2017 (Phase II). In addition, the work in Phase II includes the development and review of a variety of options available for mitigation of these emissions and the development of a set of recommendations, consisting of options which appear likely to combine feasibility with effectiveness, in reducing Hawai'i's non-energy greenhouse gas emissions. We have been aided in this endeavor by an extensive list of individuals (Appendix A) that have given considerable time and effort to answering our many questions. We greatly appreciate and acknowledge the cooperation and assistance of these contributors.

A note on units: All tonnages in this report are English (avoirdupois) rather than metric tons, and are presented in terms of compounds rather than elements (e.g., CO_2 rather than C).

II. SUMMARY OF PHASE I CONCLUSIONS

Non-energy greenhouse gas emissions from Hawai'i appear to have declined steadily since 1989, as can be seen in Figures 1a and 1b. These graphs do not account for changes in forestry management and land use, since state and county records are spotty to nonexistent regarding this subject. Forest use is unlikely to have undergone much change over the last 20 years, during which time no commercial logging has taken place on state or county land. Some sandalwood and koa logging has occurred on private land (Applegate, 1990, p. 10), but the affected area is almost certainly too small to have had any noticeable effect on statewide greenhouse gas emissions. Agricultural land, on the other hand, has undergone substantial change during this period, through loss of land area to urban development and loss of production from the remaining land area. Both of these would result in a decrease of emissions from agricultural lands, and the ensuing overgrowth of abandoned land by weedy plants would actually cause a net carbon uptake, as discussed in the Phase I report. Although sugarcane cultivation has recently been discontinued over a large area, the currently overgrown lands will eventually be put back into production for other crops and increases in carbon uptake will cease.

Although these recent forest management and land use trends lend support to the trend in Figure 1a, one important caveat reveals the deceptiveness of this apparent decline. As can be seen in this figure, the large majority of non-energy greenhouse gas emissions in Hawai'i over the last 15 years have been from landfills and the Waipahu incinerator. However, this incinerator was replaced by the H-POWER waste-to-energy plant in the early 1990s, and O'ahu's largest landfill--Kapa'a Landfill--began burning its methane for power during this same period. Thus, the overall downward trend of non-energy greenhouse gas emissions is due in part to these emissions moving over to the energy sector. This is described in more detail in the Phase I report.

Figure 1a. Non-energy emissions in Hawai'i of all greenhouse gases (1983 - 1994), excluding forestry management and land use changes. Logarithmic scale used to display trends in non-landfill sectors.

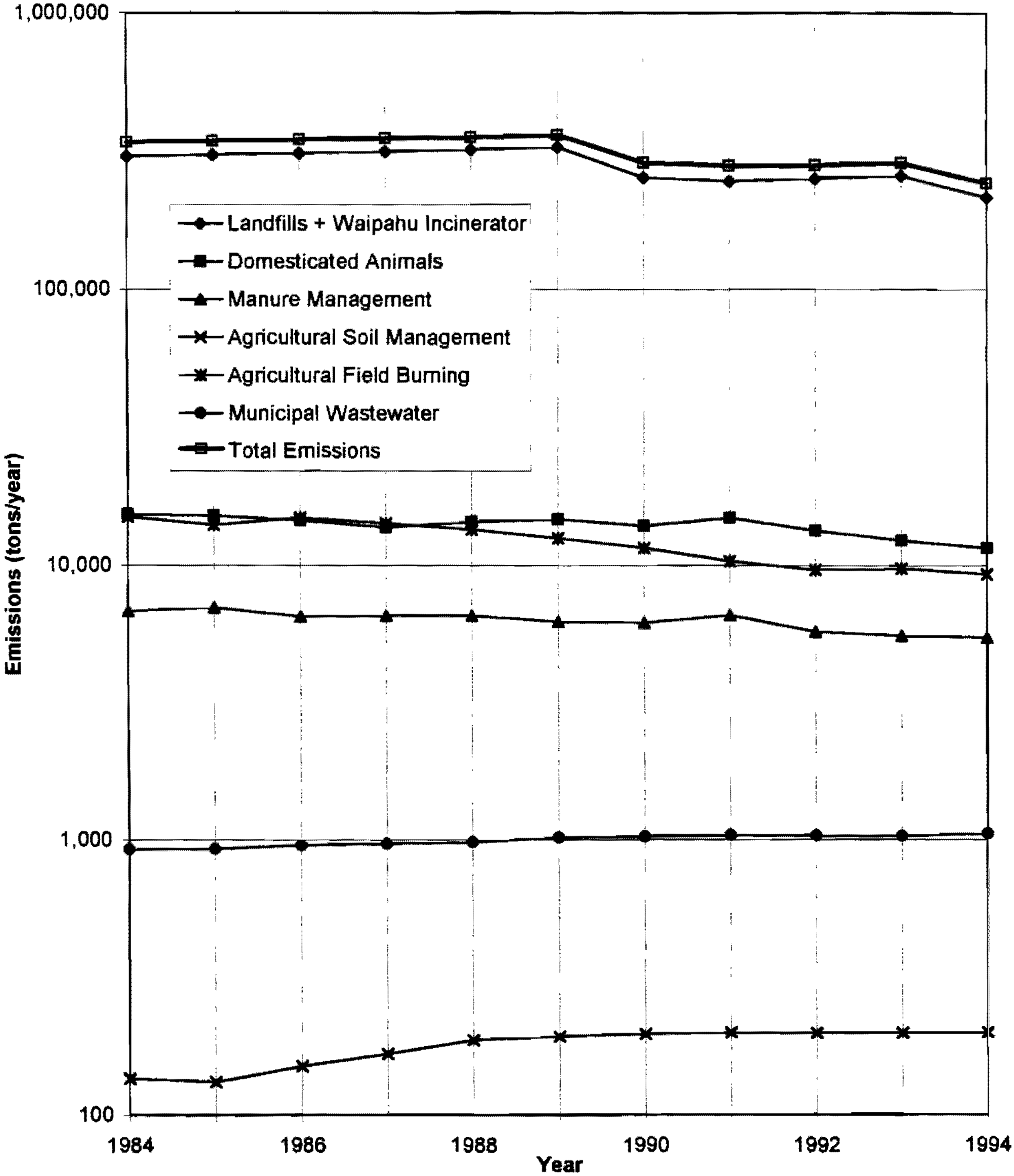
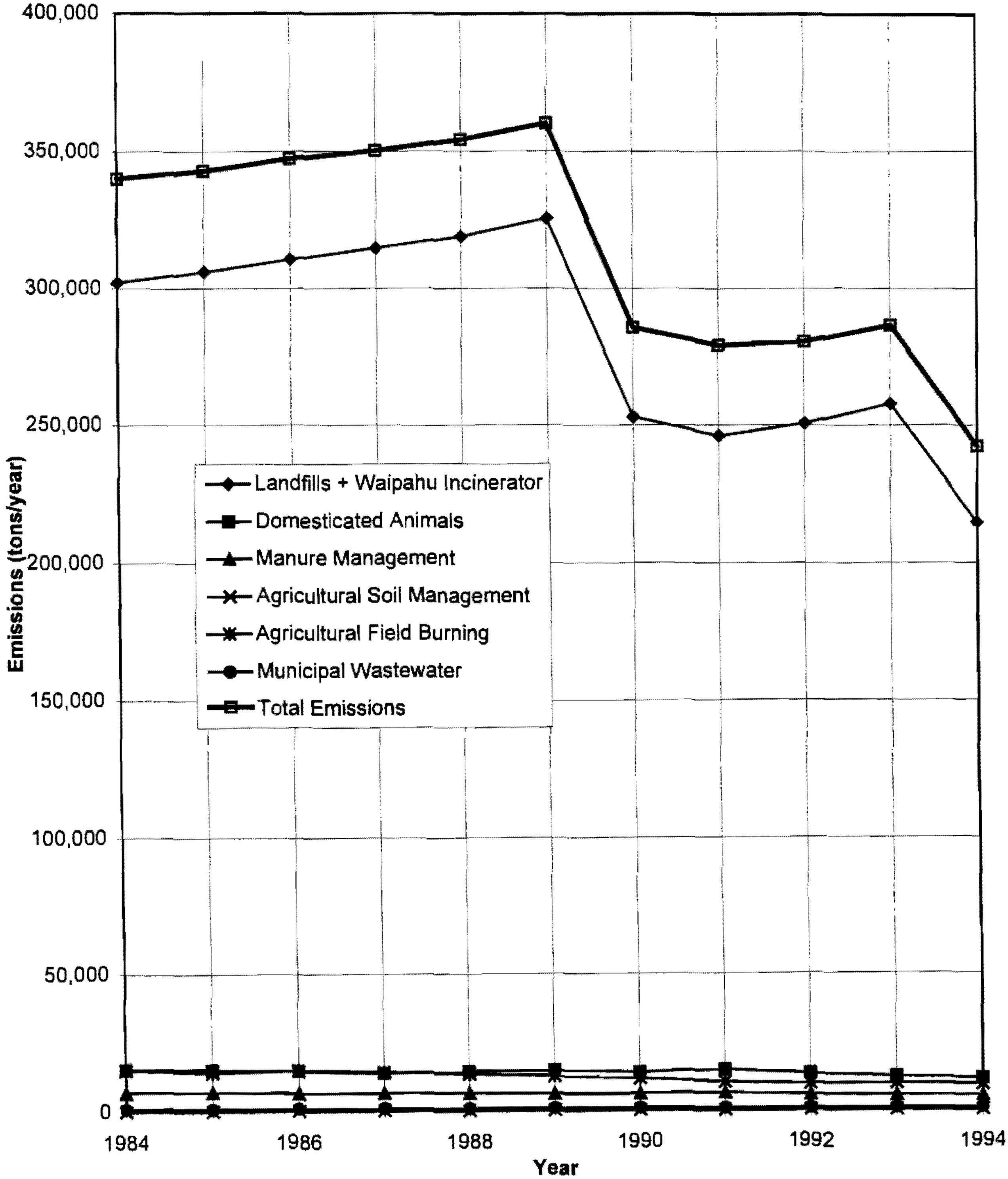


Figure 1b. Non-energy emissions in Hawai'i of all greenhouse gases (1983 - 1994), excluding forestry management and land use changes. Substantial drop in 1990 is due to startup of H-POWER plant and Kapa'a Landfill methane capture facility.



III. EMISSIONS FORECAST TO 2017

The current economic uncertainty in Hawai'i makes long-term (20-year) forecasts of greenhouse gas emissions a difficult task. Nevertheless, certain scenarios can be modeled with reasonable certainty. For this report, CO_2 emission trends have been forecast for two sectors (Figures 6 and 7), methane emission trends for seven sectors (Figures 2, 3, 4, 5, 6, 8 and 9), and N_2O for one sector (Figure 6). For most of the non-energy greenhouse gas source types in Hawai'i, possible future trends can be divided into four scenarios: (1) Those which are likely to occur if there is no change from current practices, (2) those which are likely if planned future changes take place, (3) those which are likely if the recommendations prioritized into this report's Action Plan are implemented, and (4) those which are likely if all of the technically feasible options considered in this report are implemented. For the third and fourth groups of trendlines, the reader may need to consult the following sections in order to understand the rationale behind the positioning of these lines. Some forecasts—such as those for crop burning and sewage treatment—have no fourth trendline, since all feasible options are recommended One forecast--that of methane emissions from landfills--adds a fifth trendline, estimating how landfill emissions would have increased if the H-POWER waste-to-energy plant and the Kapa'a methane-to-energy plant had never been built (Figure 2). Detailed spreadsheet calculations for the baseline landfill emissions are given in Appendix B.

Placement of these lines is fairly straightforward for some sections, especially landfills and sewage treatment plants, which are moderately well regulated. For others, especially land use and manure management, forecasts acquire high degrees of uncertainty, and should be considered as best estimates only. Mitigation of greenhouse emissions from agriculture and forestry depends to a high degree on political actions such as implementation of regulations, subsidies, tax incentives and education programs.

Emission trends are forecast to the year 2017. For the sake of simplicity, it is assumed in trends 3 and 4 that our recommendations are implemented five years from the current date, or in mid-2002. This also simplifies the benefit/cost analysis, which considers a ten-year time frame from 1997 to 2007, with 2002 as the midpoint.

It may be concluded from viewing these forecasts (Figures 2 to 9) that opportunities remain for significant additional reductions in Hawai'i's greenhouse gas emissions. However, some aspects of these graphs require some explanation.

Figure 2 displays the projected methane reductions resulting from (a) flaring or burning for power all collectable methane from landfills, and (b) all other solid waste management measures suggested above. The predicted trend that methane emissions would have taken without the presence of the H-POWER plant is also presented. In reality, the top two lines in this graph are probably lower than indicated in Figure 2, because methane emissions from landfills—as well as avoided emissions from incineration—in warm temperate areas, tend to peak and then decline at around the 20-year mark. As a result, the actual methane emissions from landfills are probably lower than they appear in this graph.

Figure 2. Calculated and projected methane emissions from solid waste management in Hawai'i, 1980-2017. Also shows the impact which the H-POWER plant has had on the state's landfill loading rate.

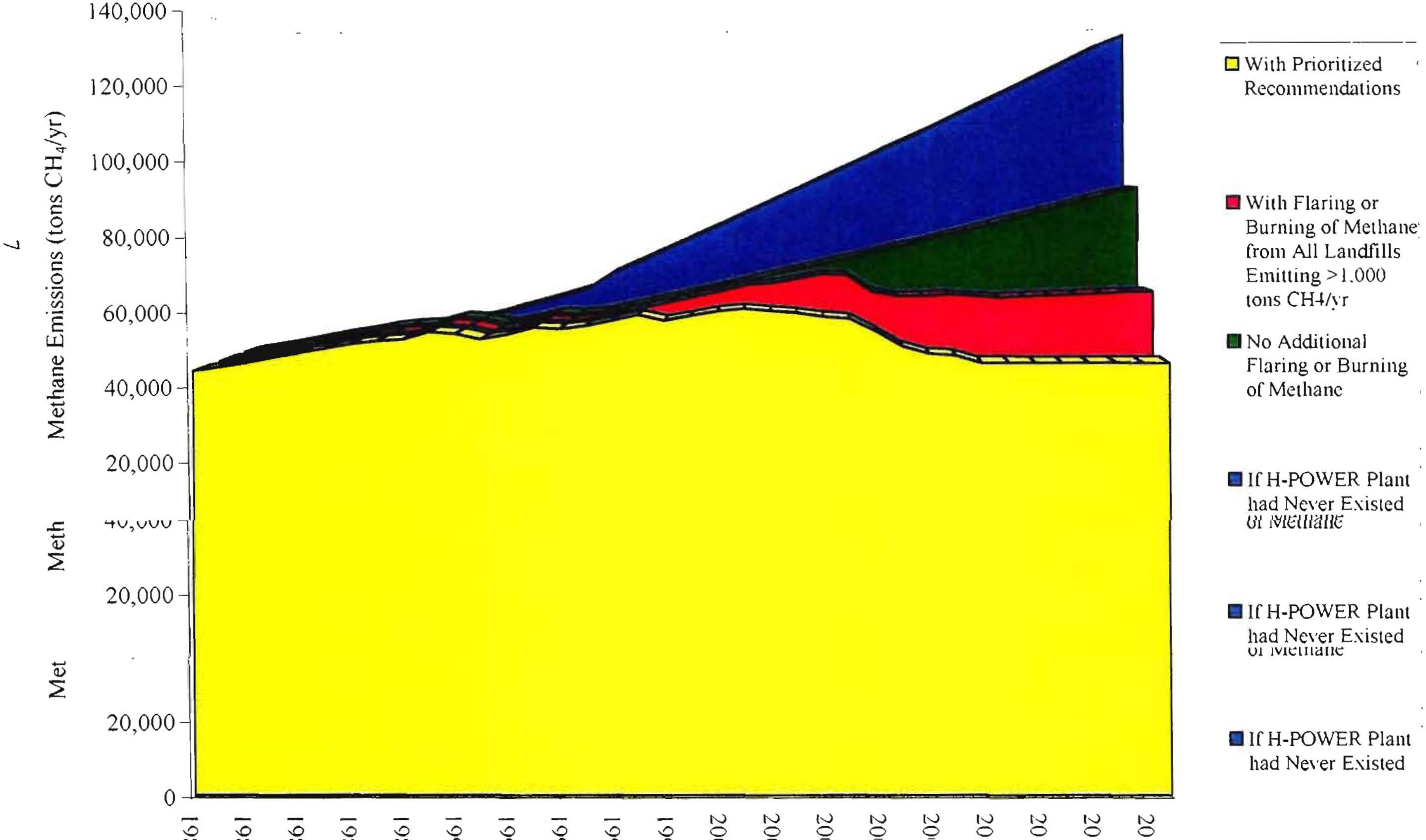


Figure 3. Calculated and projected methane emissions from cattle in Hawai'i, 1984-2017: Trend analysis and forecasting.

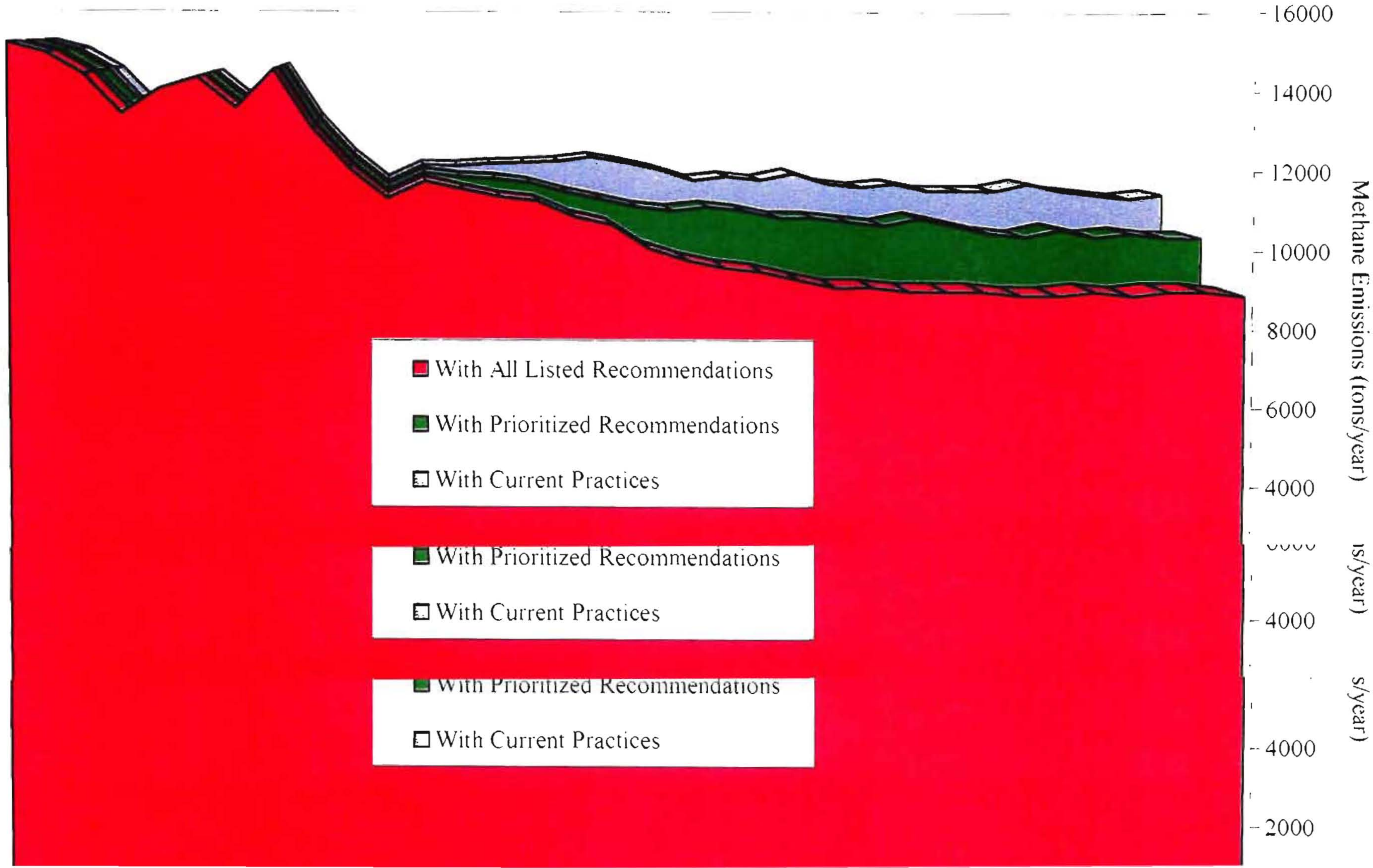


Figure 4. Calculated and projected methane emissions from swine in Hawai'i, 1985-2017: Trend analysis and forecasting.

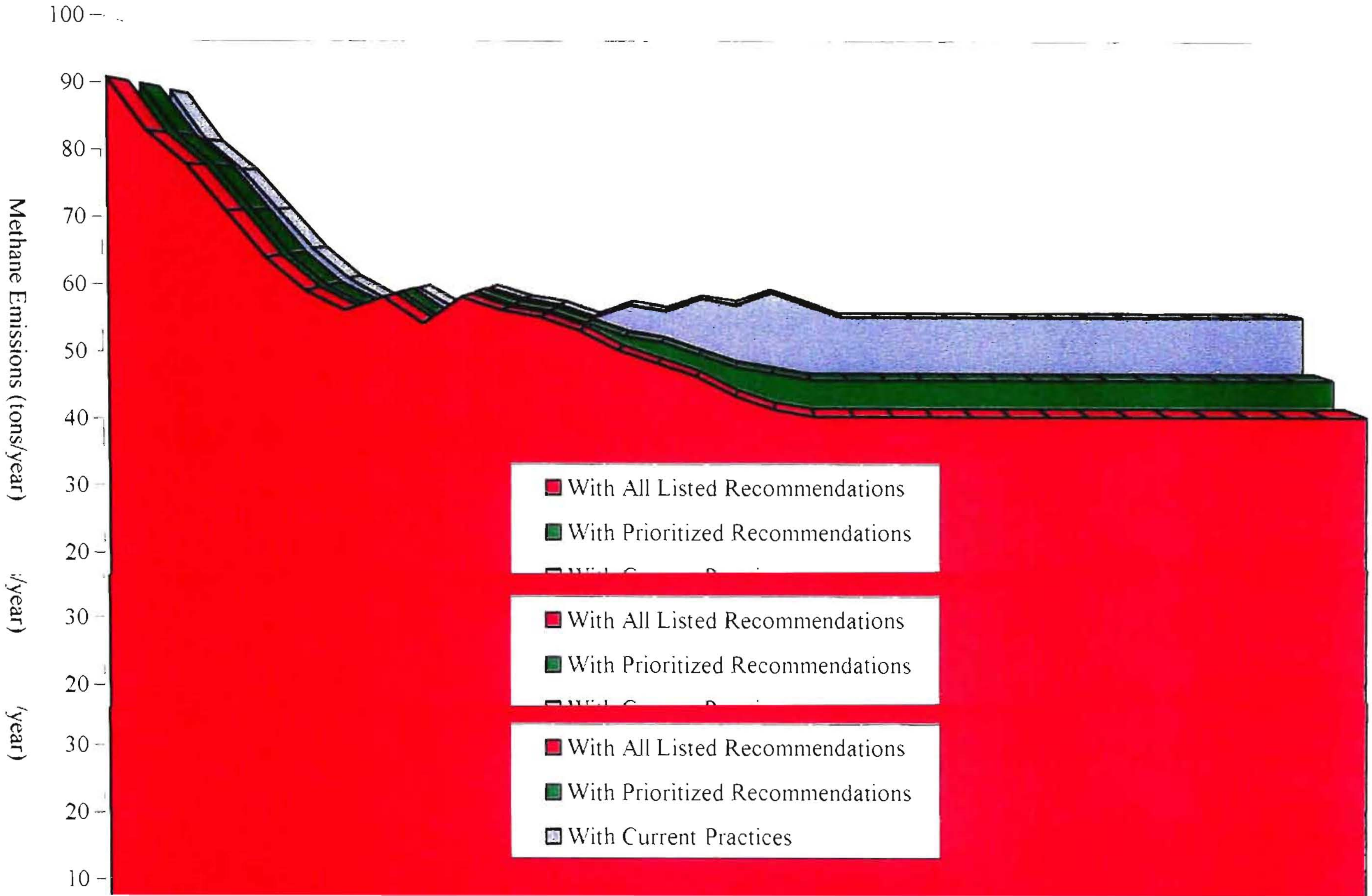


Figure 5. Calculated and projected methane emissions from livestock manure management in Hawai'i, 1984-2017: Trend analysis and forecasting.

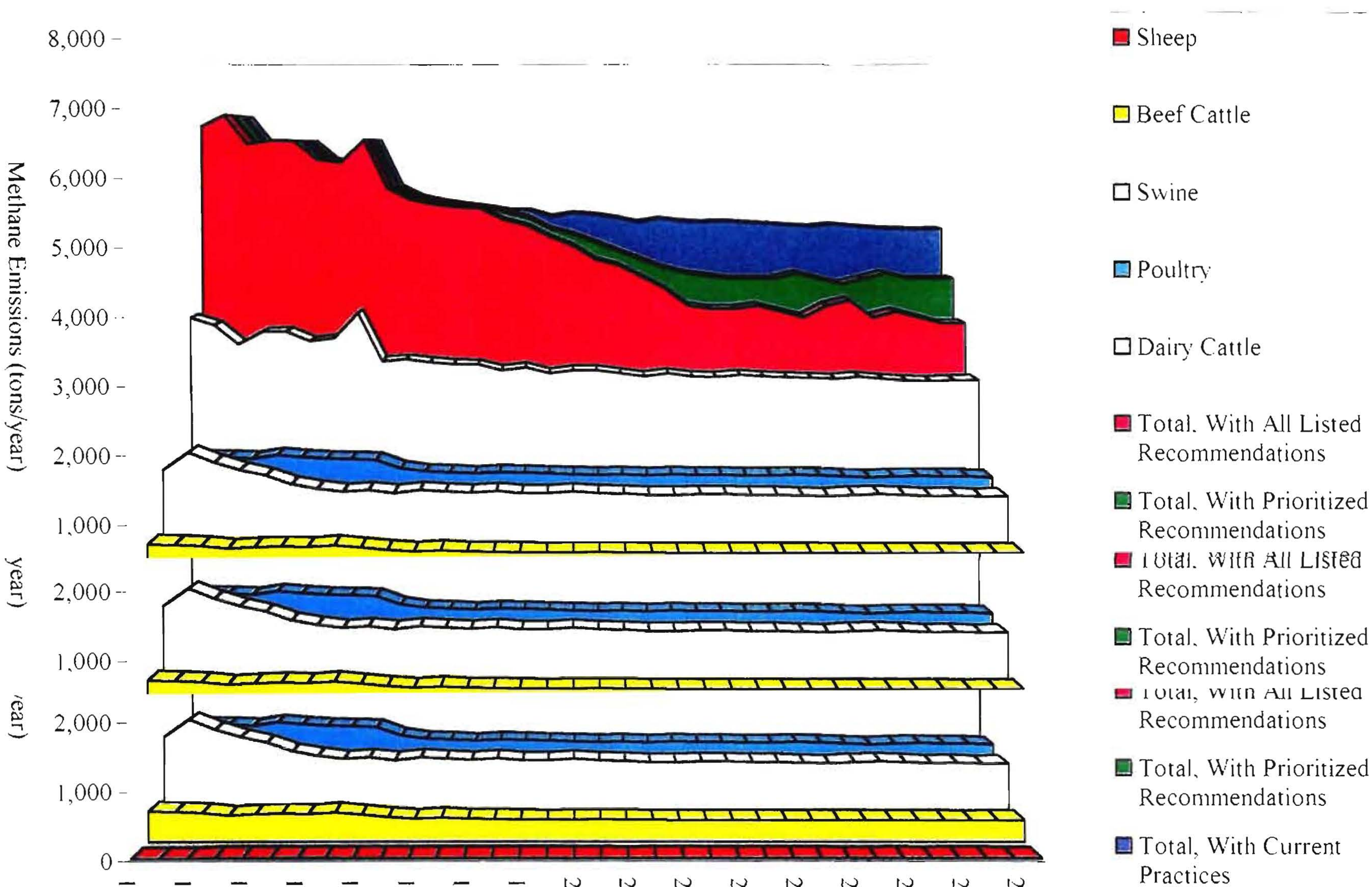


Figure 6. Calculated and projected nitrogen oxide emissions from fertilizer treatment in Hawai'i, 1984-2017: Trend analysis and forecasting.

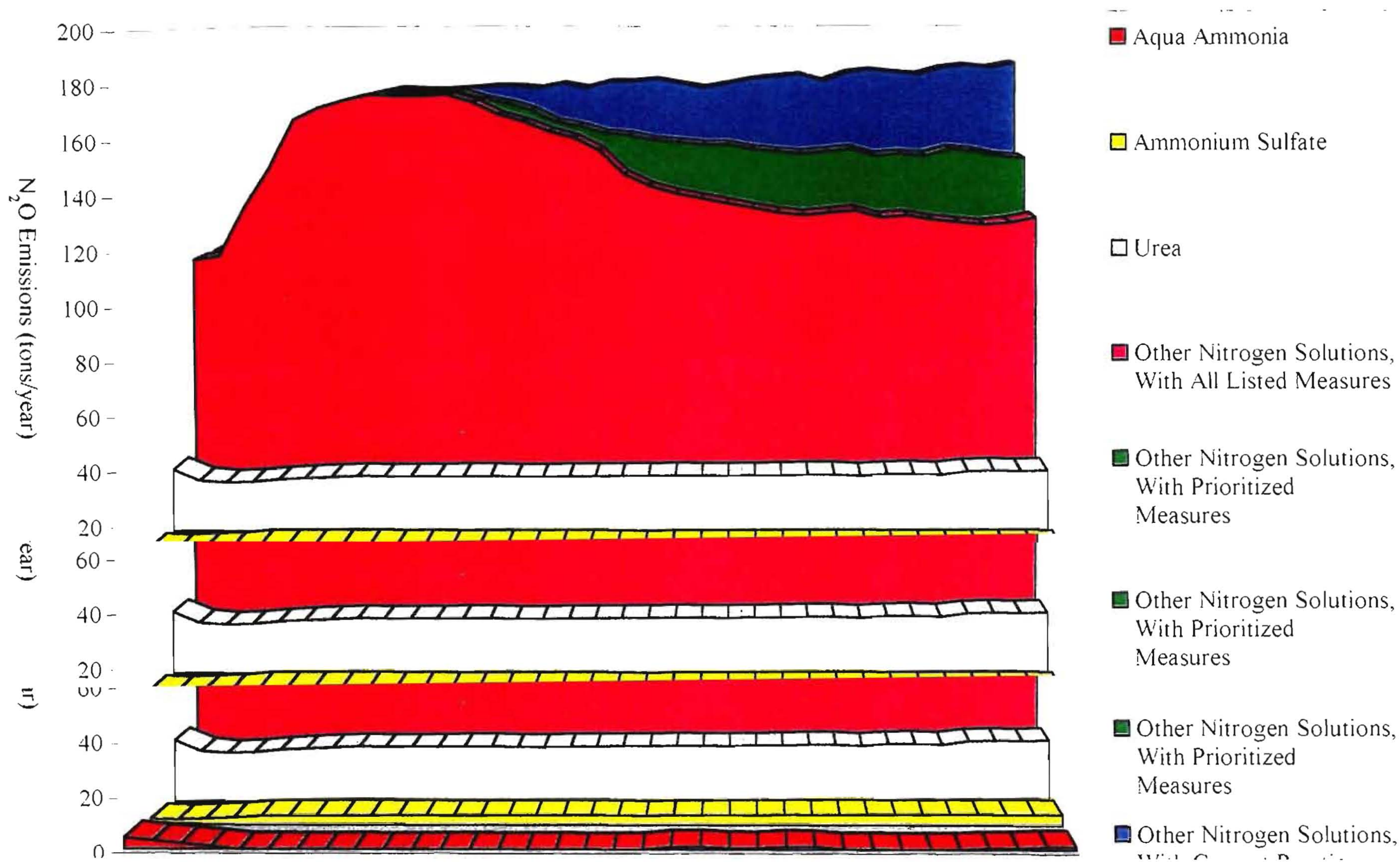


Figure 7. Projected carbon dioxide emissions from abandoned lands and managed forests in Hawai'i, 1996-2017

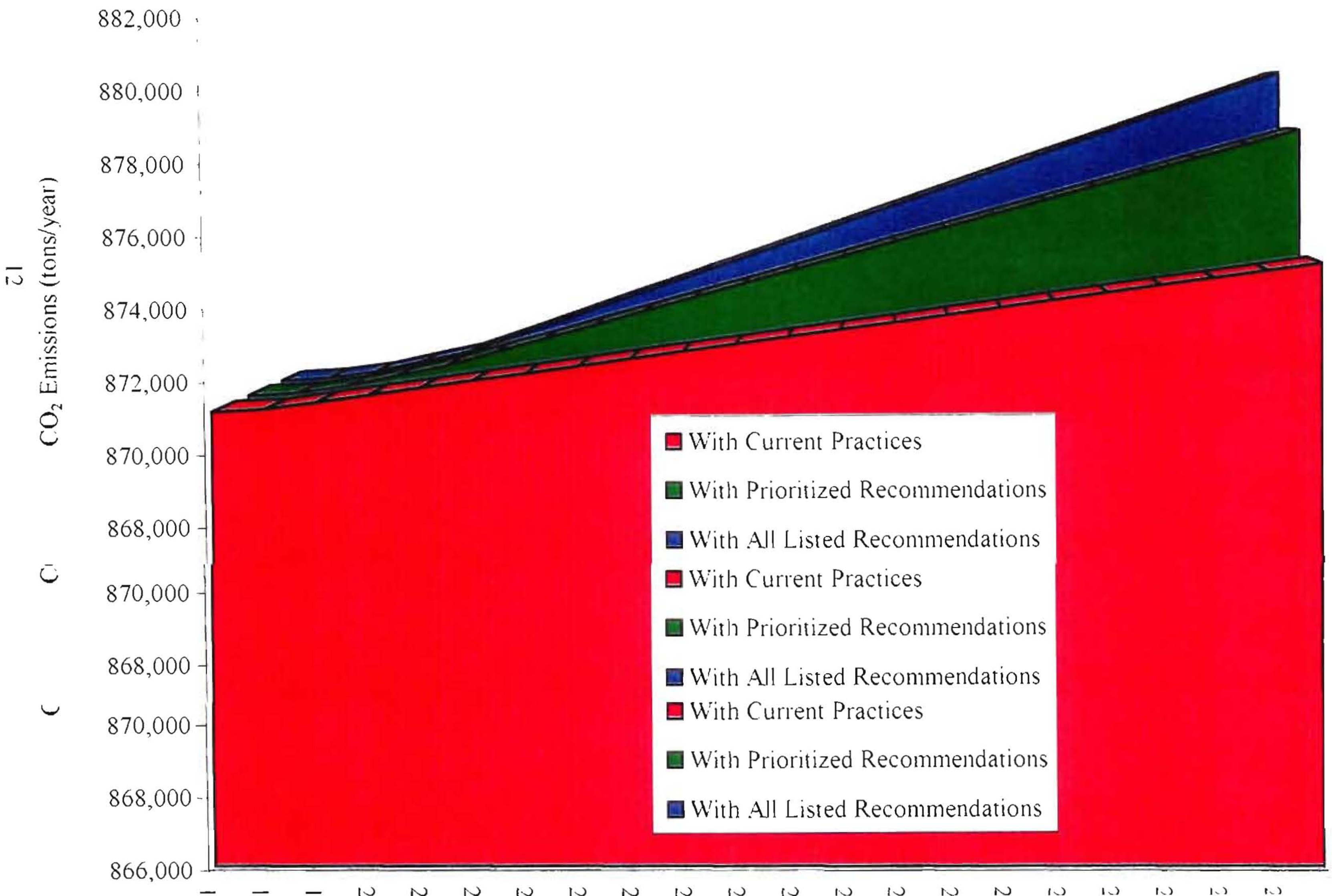


Figure 8. Calculated and projected emissions from crop burning in Hawai'i, 1980-2017.

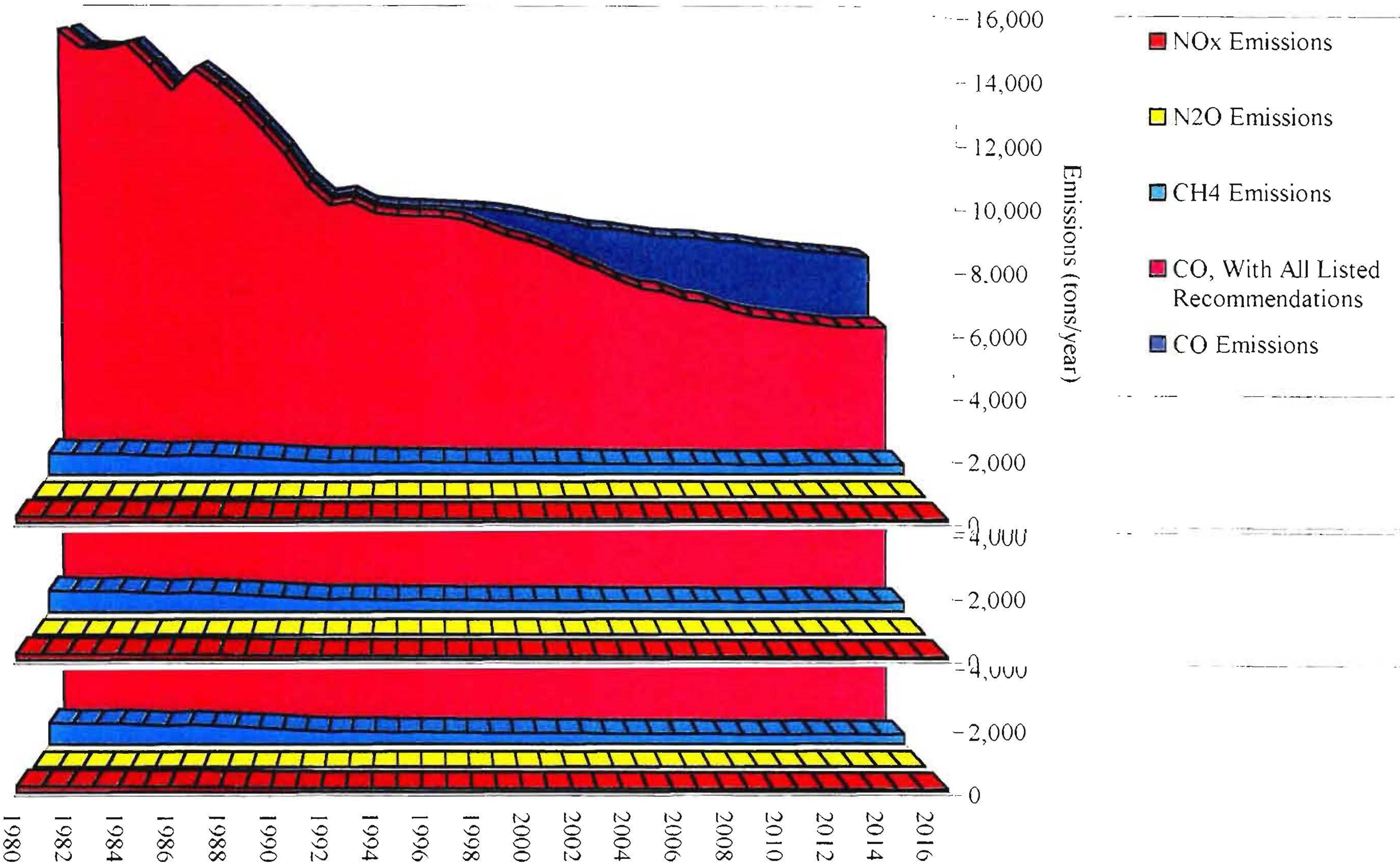
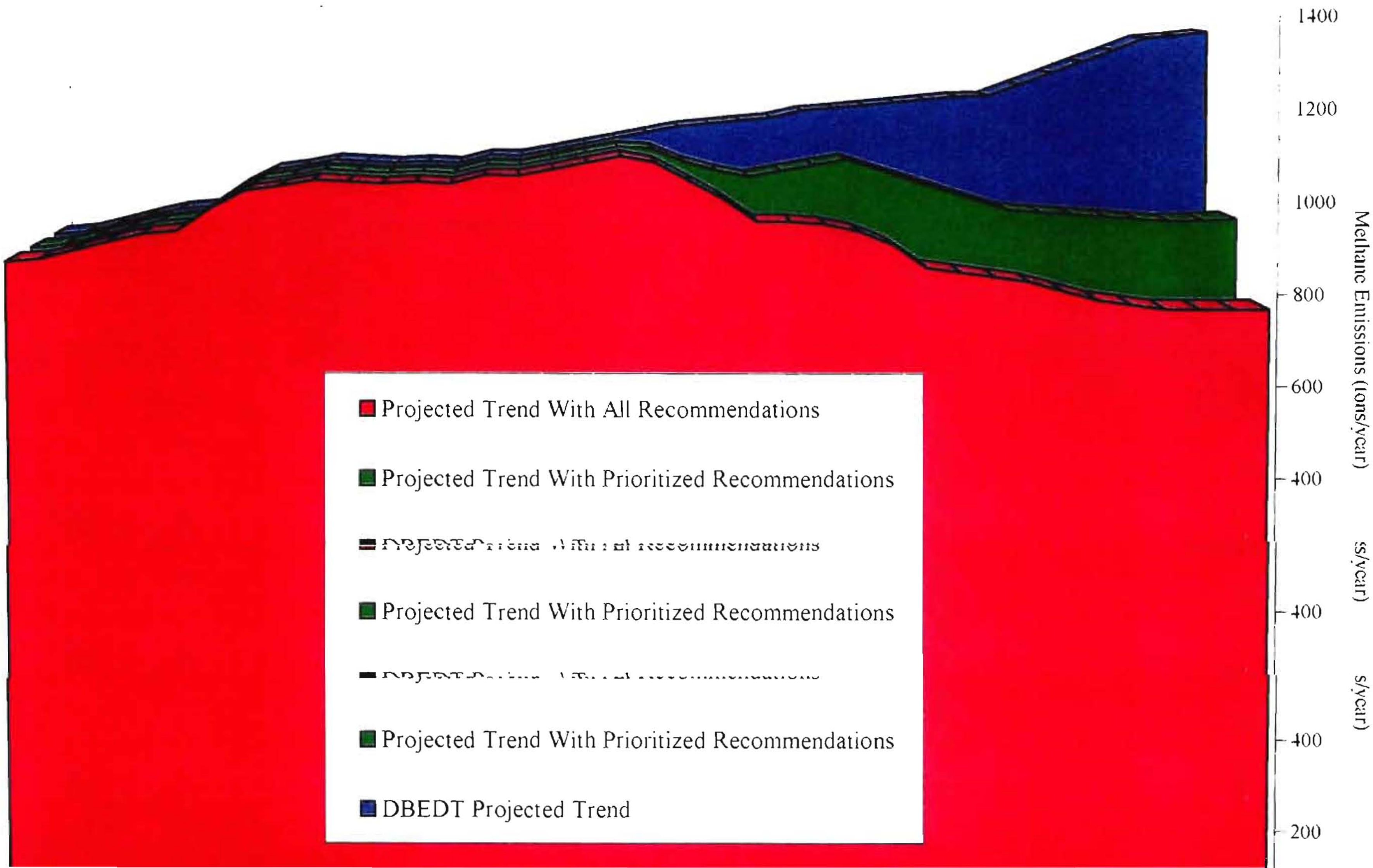


Figure 9. Methane emissions from wastewater treatment in Hawai'i, calculated from 1980 as per EPA, 1995d, p. 12-1, and projected to 2017 based on population data from DBEDT, 1997, p. 2.



On the other hand, flaring and burning of methane would have a smaller impact than what appears on the graph, since no collection system is capable of collecting 100% of the methane emitted from a landfill—indeed, a collection rate of 80% is considered exceptionally good. Difficulties in quantifying these deviations in Hawai'i from ideal conditions have prevented inclusion of these considerations in Figure 2, but these deviations would probably not change any recommendations made herein. As for the trendline showing the benefits of *all* solid waste management measures presented in the Action Plan above, this line has simply been placed so that the combination of measures will be diverting half of the annual waste stream in the year 2017, thus allowing only half the emissions that would occur with no change from present practices (Figure 2). This goal also brings the methane emissions from solid waste back down to the level they were at in the mid-1980s.

Figures 3 and 4 show trends predicting baseline (no change from current practices), prioritized (preceded by an asterisk in the Action Plan) and comprehensive (all recommendations in this sector of the Action Plan) trends for cattle and swine eructation emissions, respectively. No trends are plotted for chickens or sheep due to the minimal impact which any measures would have on emissions in these sectors.

Figure 5, for manure management measures, displays trends similar to those of Figures 3 and 4, due to both a gradual, ongoing decline in the livestock industry in Hawai'i and to the interconnectedness of the mitigation measures for these two sectors (i.e., via composting). No trendlines are plotted for chickens due to the difficulty of acquiring information regarding this rather secretive industry. Sheep are also excluded due to their low populations.

The baseline land use projections in Figure 7 follow the general trend predicted by the Hawai'i Agricultural Statistics Service, which foresees a gradual increase in managed forest acreage throughout the state—especially on the Big Island—over the next 20 years. This increase is expected to occur on both public and private land (Whalen, personal communication). The other trendlines, covering scenarios utilizing both the prioritized suggestions and the entire list of land use suggestions in this report, assume that commitments are made at the county and state level to act on local and national afforestation initiatives.

The baseline crop burning scenario in Figure 8 assumes a gradual increase in bioenergy crop cultivation, replacing sugarcane as the primary emitter of greenhouse gases from biomass combustion (Whalen, personal communication). This increase will be slowed somewhat if the industry concentrates more on long-rotation species such as eucalyptus. This graph only has one other trendline, since all recommendations in the Action Plan have been prioritized.

For wastewater management, the projected "prioritized recommendation" trendline in Figure 9 assumes (among other things) a 35% reduction in statewide methane emissions if each county establishes one anaerobic WWTP in the next 20 years, serving its largest urban area. Further reductions—to about half the projected methane emissions if no mitigation was attempted—are considered possible if the state and counties cooperate in installation of equipment to inject CO_2 into wastewater effluent exiting at deep-water outfalls.

IV. RECOMMENDATIONS

The EPA has estimated a monetary benefit accruing from reduced emissions of carbon into the atmosphere. This value is between $5 and $20 per ton of carbon avoided, calculated as the cost of removing that carbon once it enters the atmosphere. For alternative energy projects, a few relevant examples of which are discussed in this report, this is estimated to translate into $0.007 to $0.028 per kilowatt hour (kWh) (EPA, 1993b, p. 4-47). However, these values fail to take into account the variation in global warming potential (GWP) between the various gaseous forms of carbon (i.e., CO_2, CO and CH_4). Thus, these values are not included in this report, although the reader is free to apply them to the tables that follow to get a more accurate estimate of the total costs and benefits of various methods to reduce greenhouse gas emissions.

As a result of the above omissions, the benefit/cost analyses in this report are necessarily incomplete. It is difficult if not impossible at present to put a full monetary value not only on the benefits of decreased global warming, but also on the less quantifiable benefits such as reduced odor and improved safety at landfills, and reduced generation of pollutants at sewage treatment plants. Hobson and Wheatley (1993, p. 227-228) make note of this in their discussion of digesters for livestock effluents:

> *Decreased polluting power of digested effluents is a main benefit of digestion, but its monetary value is not always easy to quantify. This has been one of the problems of farm-waste digestion over the last ten years. In many cases the penalties for odor or other pollution have not been severe or have been non-existent. No monetary value has, then, been placed on the pollution control achieved by digestion: Tthe digester has been costed on the value of the biogas as farm energy and this, in turn, has depended on prices and availability of other fuels. The net result has in many cases been an apparently adverse costing for digesters.*

Quantified benefits thus consist mainly of profits from sale of energy, compost, etc. Since these vary from place to place and from customer to customer, all comparisons in this report rely on best estimates taken from ranges of possible values. In addition, even the costs for any one measure will often differ between the public and private sectors (State of Hawai'i, 1991, p. G-7). Costs and benefits not considered in this report include, for alternative energy-generating ventures: (1) a federal tax of 34% on profits; (2) a state corporate tax of 6.4% on profits; (3) a state excise tax of 5% on sales; and (4) a federal tax credit of 1.5 cents per kilowatt hour (kWh) of electricity sold during the first ten years of operation (PICHTR, 1995, p. v).

All of the following recommendations can be aided by government incentives and public/private cooperation. For example, successful efforts could be rewarded by some type of official recognition by the state and/or county governments. This will be detailed further in some of the sections of this report.

This document has been organized into different sections, but many recommendations overlap and affect one another. In terms of administration, none of these sectors are handled by a single state or county office. Thus, most of the emissions reduction recommendations in this report apply across various government departments. Numerous government officials are informed regarding the global warming issue; however, until the establishment of offices or programs which deal with composting, recycling, etc., there will be relatively limited success in reducing carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions.

Finally, the reader should be aware that methane and N_2O have higher global warming potentials per molecule than does CO_2. In other words, a ton of methane and a ton of N_2O both have significantly greater ability to increase atmospheric temperature than does a ton of CO_2. For example, if a choice exists between two alternatives for emissions reduction, one which eliminates a ton of CO_2 per day and another which eliminates a ton of methane per day, added weight should be given to the measure which reduces methane emissions.

A. Source Reduction, Recycling and Landfills

For the U.S. as a whole, landfills have been the single largest source of anthropogenic methane emissions (up to 40% of the total) throughout the 1990s. These emissions have begun to decline, however, due to a combination of pre-consumer and post-consumer solid waste reduction, and to increased capture of methane emissions from landfills (Energy Information Administration, 1995, p. 35). In 1990, the U.S. Environmental Protection Agency (EPA) announced goals of 25% solid waste reduction nationwide by 1995 and 50% reduction by 2000. In light of the fact that current efforts fall far short of this goal, the EPA now recommends only 35% reduction by the year 2005 (Harder, personal communication). The EPA recently ranked its hierarchy of important components of reduced emissions from landfills. Source reduction and recycling top the hierarchy, followed by composting, incineration and landfilling (ICF Inc., 1997, p. ES-1; see Table 3).

The state of Hawai'i's 1991 Waste Management Plan, which is up for review in 1998 by a task force consisting of both public and private entities, recommends most of the same measures as does the EPA. This plan emphasizes, in decreasing order of importance: Source reduction, recycling and bioconversion (composting and mulching). Source reduction is stressed most strongly "because it reduces costs, conserves energy and resources, and even increases national economic competitiveness" (State of Hawai'i, 1991, p. ES-1 and G-1). These recommendations seek to achieve 50% waste reduction by the year 2000. Although this goal will certainly not be met, the tonnage of waste being hauled to landfills or to combustion facilities statewide has been steadily decreasing in recent years. On O'ahu, it is estimated that nearly 10% less waste will go to landfills or waste-to-energy plants in 1997 than in 1991, the peak year for such generated waste (Jones, personal communication).

Specific waste reduction efforts in Hawai'i have been left to the individual counties. Hawai'i's four county waste management plans tend to emphasize, in decreasing order: Composting, paper recycling, and source reduction. This is the exact opposite of the order recommended by the state. Although counties have emphasized composting, due mainly to the relative ease with which it can be separated from other solid waste at the source, recycling has actually formed the greatest proportion of reduced waste tonnage in recent years (Figure 10; Harder, personal communication). As can be seen in Figure 11, a combination of paper recycling and composting can have a major impact on the volume of waste which goes to landfills or waste-to-energy plants.

The discussion below takes a more comprehensive view than the Hawai'i Waste Management Plan, instead considering in turn each of the following five options: (1) pre-consumer source reduction such as reduced packaging, (2) post-consumer source reduction such as recycling and composting, (3) waste-to-energy plants, (4) flaring of methane emitted from landfills, and (5) using this emitted methane to create electricity or steam. Various methods to accomplish these options are discussed below, followed by a summary and prioritization of the five options.

1. Pre-Consumer Source Reduction (low cost, high benefit)

Source reduction of municipal solid waste (MSW) is perhaps the easiest and most straightforward method of reducing methane emissions in Hawai'i at present. Source reduction can occur either prior to the sale of goods to the consumer, or at the time that refuse is discarded by the consumer. Producers of goods can be encouraged to reduce packaging of these goods in various ways, including:

a. *Educate local commodity producers and importers regarding the desirability of reducing packaging volume for commodities.*

b. *Government agencies themselves can increase their efforts to buy in bulk, or to request packaging which uses recycled materials.*

   For recycled paper, national studies have shown that recycled paper generally costs 1% to 2% more than virgin paper—a difference which may require changes in bidding processes for procurement contracts (State of Hawai'i, 1991, p. G-2).

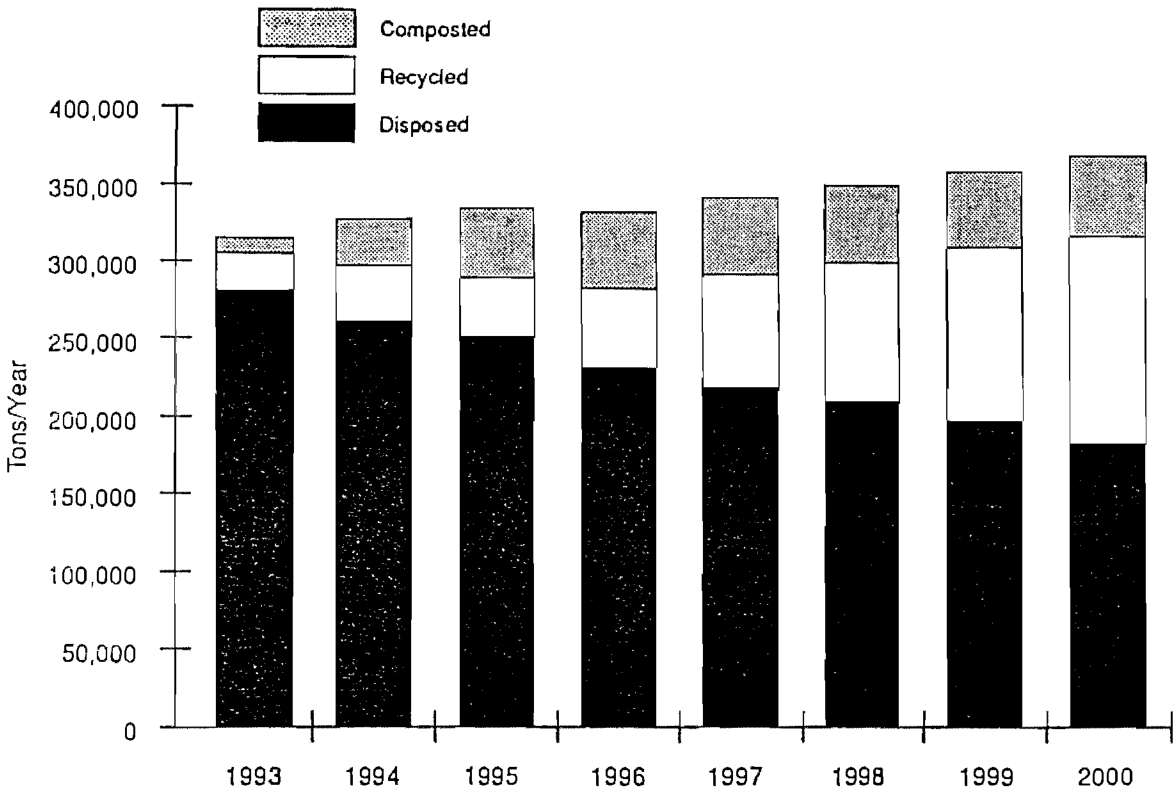
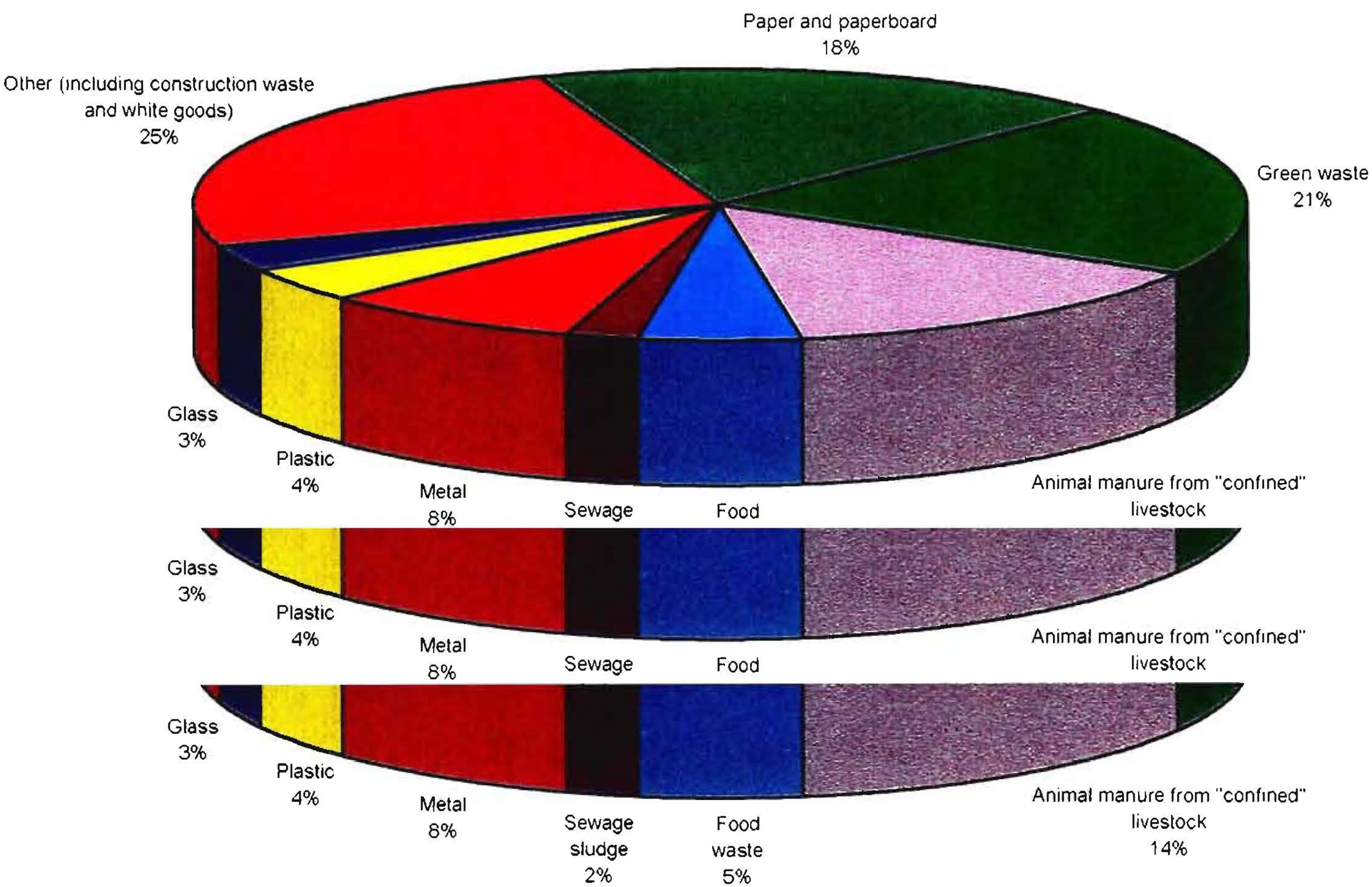


Figure 10. Predicted impact of Maui County recycling and composting programs, 1993-2000. This is remarkably similar to the actual trend. From County of Maui, 1993, p. xvi.

Figure 11. Estimated composition of waste generated in Hawai'I, 1991. Does not include greenwaste from agricultural activities. Total is 98% due to rounding. From Hollyer et al., 1996.



c. *Require all new copy machines in government offices to be capable of making two-sided copies.*

This could build on the program already underway to reduce paper used by copy machines and to increase the recycling of the paper that is used. This program is coordinated by DBEDT (McCabe, personal communication).

d. *Provide forms to businesses and residences to use to remove themselves from junk mail lists.*

Junk mail is a major contributor to paper waste generated by both businesses and residences, and its elimination would have the additional benefit of improving the efficiency of mailrooms in private and public operations (State of Hawai'i, 1991, p. G-4). This could dovetail with the program already being implemented by the County of Kaua'i, which specifically recycles junk mail from residences (Tanegawa, personal communication).

e. *Establish and implement a "green packaging" label which ensures that producers have used minimal packaging volume and/or substantial percentages of recycled materials in their packaging.*

This would be similar to other "green" labels currently in use elsewhere (State of Hawai'i, 1991, p. G-4 and G-5). However, the state claims that such a program would be impossible to enforce due to geographic variations in the source regions, nor would it be cost-effective. The state has not ruled out this option, but it is currently not considered feasible (McCabe, personal communication). Yet this lack of feasibility may not apply to locally-produced products. Indeed, the state itself has suggested such a label for local manufacturers (State of Hawai'i, 1991, p. G-6).

In addition, counties can now invest more resources into recycling due to increased funding from the state and to procurement commitments. As an example of the latter, the State Department of Accounting and General Services (DAGS) now ensures that 25% of the paper it purchases consists of at least partly recycled material, a percentage that may rise close to 100% due to a joint effort by several western states to buy recycled paper in cost-effective volumes (McCabe, personal communication). Such efforts can act as both an incentive and as a model to counties considering similar joint efforts for purchasing recycled materials and for recycling the materials which they use. Indeed, a reciprocal relationship could be established, since the tonnage of material recycled by the counties would be more than sufficient for state government needs, although most of the material (e.g., white paper, newspaper and cardboard) must be first sent outside the state for the actual recycling process. The City and County of Honolulu is even promoting the Made in Hawai'i Festival, part of a national campaign to buy locally-recycled materials. This bodes well for future procurement commitments.

Although these measures would help to reduce the amount of solid waste entering agencies, businesses and homes in Hawai'i, they will have limited effect if the markets and consumers are not themselves educated about their efficacy. Commercial centers, especially supermarkets and commodity stores, can help reduce landfill volumes by developing and promoting reusable bags for their customers. Since there may be some reluctance on the part of customers at first, some degree of promotion would be necessary to infuse customers with enough information to understand the reasoning for these measures.

2. Post-Consumer Source Reduction (low to moderate short-term cost, high benefit)

Once goods have reached the consumer and are ready to be discarded, several options become available for reducing the volume of solid waste which individuals contribute to landfills. The most obvious is recycling, which is discussed below. Compost will be discussed later under fertilizers. Source reduction has been moderately successful in Hawai'i in recent years, with recycling alone diverting some 21% of the waste stream as of 1997. Although such reductions appear to be due more to the increasing price of virgin pulp for newspapers and telephone books than to concerted local efforts to reduce the waste stream (Harder, personal communication), significant room for improvement still remains. Indeed, the state's recycling coordinator estimates that 35% of the waste stream will likely be recycled as of 2007 (McCabe, personal communication).

However, even if Hawai'i's recycling rate continues to increase, it may have little effect on the organic content of landfill material. Indeed, nationwide the EPA has predicted that the organic content of landfill waste will increase slightly in the coming years due to: (a) increased per capita consumption of paper, wood and other organic components, and (b) increased efforts to recycle noncombustible materials such as aluminum and glass (EPA, 1993a, p. 4-26). This may actually be good news for those landfill operators whose landfills are near the lower end of the range within which methane can be economically collected for power generation (see Composting section below).

Since only about 6% of the organic portion of Hawai'i's waste stream is being recycled at present (Hollyer et al., 1996), there is room for fairly substantial increases in organic recycling. Such diversion would have various benefits to the state as a whole which would not be possible if this green waste were landfilled. Counties are now moving to implement diversion measures (McCabe, personal communication), and the green waste recycling percentage should increase dramatically in the coming years as a result.

The following recycling measures are suggested:

a. *Support county recycling programs and improve coordination efforts and internal programs of state government offices.*

Recycling efforts in Hawai'i vary widely from county to county. Maui has initiated islandwide sewage sludge (hereafter biosolids) and green waste composting, and has banned disposal of biosolids in landfills since 1996. The recycling rate reached 24% in 1996 (Hirose, personal communication). Most materials are recycled via drop boxes, but the private operation Maui Recycling Service charges $17 per month for home pickup of all recyclable materials. This includes green waste, which is brought to Echo Composting on the site of Maui's Central Landfill, where it is co-composted with all of the county's biosolids. Another private company, Maui Composting, plans to start composting green waste and food waste in the near future, using state startup funds (Baker, personal communication). The county composted approximately 28,300 tons of green waste, biosolids, used oil and shipping pallets in 1996, up sharply from about 18,000 tons only a year before (Cordell, personal communication). Maui has set itself the ambitious goal of recycling between 50% and 65% of its waste stream by the year 2000, through these and other operations, and through an impending county mandate requiring all businesses to recycle their cardboard and food waste (Baker, personal communication).

On O'ahu, the amount being recycled is steadily increasing, from 22% in 1995 to 26% in 1996, and is projected to reach 28% by the year 2000 (Namunart, personal communication). Expansion continues mainly due to initiation of new regulatory measures. For example, the City and County of Honolulu now bans any load with more than 50% cardboard, paper and/or green waste from all landfills and the H-POWER plant. The green waste is mulched or composted, since 1993 mainly by the private company Hawaiian Earth Products, Ltd. Straight mulch is given to homeowners and city parks for free, while composted mulch is sold for $30/lb. to $32/lb. O'ahu's state and national parks and monuments have not yet requested this mulch (Namunart, personal communication; Hawaiian Earth Products, 1995; Hawaiian Earth Products personnel, personal communication). Currently, curbside pickup of any recycled material is confined to areas receiving automated trash pickup, where green waste is picked up if left by the curb by the resident. As the percentage of the county receiving automated pickup grows (scheduled to reach 75% to 85% by the year 2000), this service will reach a higher percentage of residents. For green waste, this is projected to dramatically increase pickup tonnages, from 350 tons/year in 1996 to approximately 6,000 tons/year in 2000 (Namunart, personal communication).

On the other hand, Hawaiian Earth Products has seen a significant decrease recently in the amount of incoming green waste. At present, the company receives approximately 1,500 tons of green waste per month, mainly from private haulers, down from the 2,000 tons per month the operation was receiving in early 1995. The company places the blame on both lagging interest on the part of the community, and on lax enforcement of the county's green waste ban at the Waimanalo Landfill (Hawaiian Earth Products, 1995; Hawaiian Earth Products personnel, 1997).

On Kaua'i, the present percentage of recycling by the county alone is estimated to divert approximately 16% of the waste stream, or 200 tons per day, from landfills. This program includes a system of dropoff boxes for newspaper, cardboard, junk mail, glass and aluminum. There is also a county program to pick up green waste and tires upon request. This program diverted approximately 29,500 cubic yards of green waste from landfills in 1996, converting it to mulch which the county gave away to homeowners. Around 90% of this green waste was generated by county operations. Although a county-run composting project was attempted in 1993, it was discontinued in 1994 for various reasons (Tanegawa, personal communication). The overall recycling trend is somewhat stagnant at the moment, but the county hopes to initiate new mulching and public education programs in the near future. The mulching operation, while privately run, would use county land in Princeville. It would feed a nearby, privately-run composting operation which intends to also compost biosolids. The county is also considering bans on materials such as green waste and cardboard at landfill facilities. Together, these programs should cause Kaua'i's recycling percentage to resume its upward trend (Tanegawa, personal communication).

On the Big Island, all recycling to date has been undertaken by private entities. This makes it difficult to get a complete estimate on how much is being recycled, but the figure is estimated to be between 9% and 12%. The future trend remains unknown, due in part to uncertainty regarding the initiation of county-run recycling programs. For example, in the early 1990s, the county first started, then suspended a composting program which remains in limbo at present (Capelis, personal communication; McCabe, personal communication).

While recycling efforts necessarily will vary from island to island and from county to county, it appears that all of the counties can still learn from each other. Furthermore, the state has a role to play as a clearinghouse for information both between counties and from outside the state. The state can also urge the counties to make their recycling programs more consistent with each other, and to better educate the public through workshops, bill inserts, etc. The state can help county recycling efforts in direct ways as well. For example, the state already charges an "advance recovery fee" of 1 cent for every glass container shipped into the state. This income funds glass recycling efforts in the various counties, with $100,000 going to Kaua'i alone in 1996 (McCabe, personal communication, Tanegawa, personal communication). Similar advance recovery fees could be charged for paper, cardboard and other organic materials.

Another important step for the counties to take is an increase in tipping fees at landfills, which currently range from $37 on Maui to $55/ton on O'ahu (plus a 6% surcharge which goes to recycling efforts) (Parke, personal communication; Baker, personal communication comm.). One way to improve the community's acceptance of such a measure would be through unit pricing; in other words, "the more you throw away, the more you pay per ton" (Baker, personal communication). Although a tipping fee surcharge is not as proactive or direct an approach as is an advance recovery fee, the administrative costs of a surcharge would probably be significantly lower (State of Hawai'i, 1991, p. 7-9 and G-9).

As noted above, counties are moving to impose recycling mandates and further bans on landfilling (McCabe, personal communication). Yet substantial room remains for improvement even without these regulations on private entities. For example, although the state has passed Act 228-96, which encourages the state government to purchase locally-produced composted products, this act is not binding (Hollyer et al., 1996, p. 6). Furthermore, none of the county governments have made commitments to buy any products from local operations which undertake either composting or other recycling (Baker, personal communication). Even on Maui, where the county is saving an estimated $20,000 per month in reduced hauling fees due to the activities of Maui Recycling Service, this private operation has received little support aside from the county's gift of a collection truck. This operation, which does not generate a net profit, would benefit from commitments by the county and/or state to purchase the recycled products and/or move the excess to markets off-island (Baker, personal communication). On O'ahu, Hawaiian Earth Products has found the county to be a fairly good—if inconsistent—customer, but the state hardly ever purchases their product, preferring to use mainland compost instead.

Urban curbside recycling programs have also been initiated by more than one county, but legal or accounting hurdles tend to abort these efforts. What was arguably the largest county-run recycling effort to date provided curbside recycling pickup in the towns of Kailua and Kane'ohe on O'ahu over a period of several months in 1991. This program found strong support in the community, yet was discontinued due to inappropriate cost estimates. For example, collection vehicles and equipment costs were based on a single year of operation rather than being amortized over a standard, useful life expectancy period for such equipment (Harrison, personal communication; McCabe, personal communication). The city now has 54 drop-off bins around Honolulu, mostly near schools and primarily for educational purposes. Maui is also attempting to initiate curbside pickups, but the program has been held up for several years due to challenges in court. All of these contracts may have been delayed somewhat by lack of flexibility to changing conditions and to increasing expertise in the recycling process (McCabe, personal communication).

Some of the problem remains outside the jurisdiction of both state and county governments. In particular, the cost of shipping recovered material overseas for recycling remains prohibitive in many cases (McCabe, personal communication). Nevertheless, significant room for improvement still remains, in particular for recycling of green waste and food waste, both of which can (and, in the latter case, must) take place within the state. Efforts to recycle green waste and food waste will be discussed further in the Composting and Mulching sections below.

Costs of recycling programs include capital costs for planning and equipment, plus operating costs for transportation, marketing, labor, maintenance, administration and debt service. Benefits arise largely from the sale of recovered materials. The community benefits through savings from disposal costs and any economic stimulus which the program initiates. If the counties run these programs, such community benefits are largely internalized (EPA, 1989, p. 74). One small but important aspect of overall cost would be a program to inform and encourage the public to sort refuse by recyclable type. This cost, although ongoing, is key to the overall success of the project.

Detailed costs and benefits for county-scale recycling programs in Hawai'i remain largely unknown, as noted above. However, on the mainland rising costs for virgin paper pulp and aluminum have put many recycling programs into the black in recent years, and a private firm currently finds it profitable to undertake paper recycling for the University of Hawai'i system (Ah San, 1997). The market for compost also appears far from saturated, since Hawai'i still imports at least 12,000 tons of compost and other soil amendments every year (Hollyer et al., 1996, p. 4).

b. *Provide incentives for private recycling operations to become established, especially for organic wastes such as paper and green waste.*

Several options fall under this heading. Those most likely to be productive are, in decreasing order of benefit/cost ratio:

i. <u>Initiate bans on green waste, food waste and cardboard from entering landfills or the H-POWER plant</u>. The state Department of Health (DOH) has developed an administrative rule (Title 11, Chapter 58.1), which requires all counties to develop a plan to ban—or require source separation of—green waste from entering a disposal facility (Hollyer et al., 1996, p. 6). The counties are moving to meet this rule, but strictness and enforcement of county regulations vary. For example, recyclers on O'ahu claim that the Waimanalo Landfill has become lax recently about enforcing the county's green waste ban (Hawaiian Earth Products Personnel, personal communication).

ii. <u>Investigate increasing tipping fees at landfills.</u> Tipping fees appear likely to increase significantly anyway at present (by up to 300%), due to the current trend toward de-privatization of landfills (*Honolulu Advertiser*, June 8, 1997, p. A27). On Maui, where all open and closed landfills are county-run, tipping fees and general fund allocations generate approximately $400,000 per year for recycling operations, even with tipping fees of only $37 per ton (Baker, personal communication). However, since all landfills and the H-POWER plant now charge tipping fees (in contrast to the situation a few years ago), it is possible for the state to implement tipping fee surcharges to equitably collect monies to fund state-level waste management programs, in addition to the 25 cents/ton surcharge currently imposed to fund regulation

(State of Hawai'i, 1991, p. 7-11; McCabe, personal communication). An additional 50 cents/ton surcharge would provide approximately $500,000 per year for recycling efforts (see Table 4), while providing added financial impetus to waste generators to make use of such alternative methods.

iii. Educate businesses and residents on benefits. For the last few years, the City and County of Honolulu has sponsored the Partnership for the Environment, which brings together business leaders to share information regarding initiatives to reduce waste generation and energy use. This project has had positive results, and more are expected in the future. For example, although the Sheraton and McDonald's chains in Hawai'i have told their suppliers to cut packaging by 25%, supermarkets have yet to initiate any such programs (Harder, personal communication). State and county departments have also helped fund the Green House Hawaii Project, a non-profit program to display and promote building materials and designs which are resource-efficient, recycled and locally manufactured (Green House Hawaii, 1997).

Most promising is the creation of the Clean Hawaii Center within the Energy, Resources and Technology Division of DBEDT. This Center promotes recycling businesses and market development through funding, workshops, a "Buy Recycled in Hawaii" guide, and a checklist of permit requirements and regulations for solid waste and recycling businesses. The Center was established in 1995 and is scheduled to be terminated in 1999 (Wood, personal communication).

State and county governments can also provide waste evaluations or audits at low cost to businesses, or develop self-audit checklists for businesses and residences. However, it is difficult to provide audits at low cost, since such a program must provide the salary for a full-time professional (State of Hawai'i, 1991, p. G-5). As a result, this option is not included among the recommendations in the Action Plan presented later in this report.

iv. Educate government offices on benefits. State government offices also need to educate each other. Far-flung offices and agencies in particular tend to be out of the recycling loop. One notable effort currently underway is the DBEDT-coordinated program to reduce use of paper in—and increase recycling associated with—copy machines (McCabe, personal communication). Related measures include increasing the availability of electronic mail to state and county employees, and replacing paper towels with cloth towels (State of Hawai'i, 1991, p. G-3).

v. Government procurement commitments. See discussion above. This echoes a recommendation made by the Department of Health in 1991 (State of Hawai'i, 1991, p. ES-4).

vi. Tax breaks and low-interest loans. These incentives could be similar to what the state has offered to those installing solar water heaters on their homes.

Each of these options has potential in and of itself, but by combining them it is more likely that a profitability threshold will be reached, whereupon the last two options may no longer be necessary.

Some operations require funds only for startup fees. On Maui, the King Diesel company began in May 1997 to convert used cooking oil from food establishments into ethanol, a nontoxic and cleaner-burning alternative to diesel fuel which requires no conversion of diesel engines. This operation expects to be recycling 4,000 to 5,000 gallons of cooking oil per month by the end of 1997, out of an estimated 8,000 gallons generated throughout the county each month. Funded by the federal Department of Energy, this unique facility expects a 5-year payback period in spite of the $1.95 per gallon it charges, compared to $1 per gallon for regular diesel fuel (King, personal communication).

Other operations, such as the Maui Recycling Service, have continually operated in the red, due mainly to low demand for their products. Not only the above-mentioned government procurement commitments, but also aid in marketing and shipping recycled products would often help such companies approach self-sufficiency.

All of the above operations together would have a significant effect on the amount of methane emitted by solid waste management in Hawai'i, and most of them are recommended in the Action Plan. CO_2 reduction would be smaller, but also noticeable. Both of these are overshadowed, however, by the much larger reductions in methane emissions likely from increased flaring and burning of landfill methane for power (Figure 2). This is due in part to the fact that on most islands, recycling efforts are well underway. Many of the easy targets have already been met, and future progress in many areas will likely be incremental, a slow but fairly steady increase over the coming decade, after which the trend will level off. Landfill methane, on the other hand, is a relatively untapped resource, one which is mandated to be mitigated in all of the larger landfills in the state (Table 4). Thus, in the Action Plan, landfill gas collection gains precedence over source reduction and recycling in Hawai'i.

3. Construct and Operate Waste-to-Energy Plants (moderate to high short-term cost, moderate benefits)

Currently, the only waste-to-energy plant operating in Hawai'i is the H-POWER plant at Campbell Industrial Park, O'ahu. Although other sites have been considered in the past by the operators of the plant and by the various counties, no additional plants are currently planned (Jones, personal communication). Traditional waste-to-energy plants can be divided into two types: Mass-burn and refuse-derived-fuel (RDF) types. Mass-burn plants process MSW without sizing, shredding or separation, aside from perhaps bulky items like refrigerators and hazardous materials such as car batteries. RDF plants classify and shred the waste, increasing its heating value and allowing some materials to be recycled. There is no significant difference between these two on the basis of CO_2 generated per ton of refuse; however, RDF plants produce significantly lower tonnages of other air pollutants such as NO_x and CO (California Energy Commission, 1991, p. 5-92). These plants still produce ash, however, which must be landfilled. The H-POWER plant is of the RDF type, and is currently running near its capacity of 650,000 tons per year.

The market for waste-to-energy plants in Hawai'i appears to be already at or near saturation. The H-POWER plant already combusts approximately half of all solid waste generated in the state, and has generated a net profit only because the large majority of Hawai'i's solid waste is generated on O'ahu. The only other possible candidate at present is Maui, but the approximately 150,000 tons of solid waste produced annually on that island falls well short of the 210,000 tons/yr considered to be the bottom line for supplying a profitable waste-to-energy plant in Hawai'i. Collecting waste from various islands is also prohibitive due to high transportation costs. The best alternative at present appears to be reconverted sugar mills such as the one currently being tested at Pai'a, Maui (discussed below under Crop Burning), which will eventually burn approximately 35,000 tons/yr of biomass, green waste and used cooking oil (Jones, personal communication; Parsons Brinckerhoff Quade and Douglas, Inc., 1995, p. 7-1 to 7-5).

An intriguing alternative to H-POWER and converted sugar mills is a plant which goes by the name of HITECH, or the Hawaiian Integrated Technology Plant, scheduled to be built on the south coast of Kaua'i by Coxwell Energy, Inc. and be operational by 2002. This plant would use state-of-the-art technology to convert 300 tons of MSW per day (105,000 tons/yr) to 10 megawatts (MW) of energy after subtracting energy which the plant itself requires. Waste would be vaporized by a plasma arc at 15,000^{o} F, leaving only synthesis gas and vitrified glassy rock. The gas would be used to power a turbine, and the rock could be crushed for use as a road aggregate or poured into molds for building material (Coxwell Energy, Inc., 1996, p. 1-2). According to the developers, some 56 of these plants are already in operation or scheduled for completion worldwide in 1997, the largest producing 107 MW of energy (Coxwell Energy, Inc., 1996, p. 18-20). The operators of the HITECH plant even intend eventually to begin mining the existing landfills on Kaua'i for fuel as well, thus reducing and ultimately eliminating the methane emissions from these sources. Financing for the plant would be through tax-free revenue bonds guaranteed by the state government and paid back through plant revenues (*The Garden Island*, September 6, 1996, p. 1-2).

Yet questions have been raised regarding the capability of such a plant to produce the net 10 MW (originally 14 MW) which it currently promises. More than one source has claimed that the developers have based their energy production predictions on overestimates of the heat energy of solid waste and the volume of solid waste which the plant would receive. As a result, the HITECH plant may only produce enough energy to power itself, with none left over for sale (Tummons, 1997; Jones, personal communication). If no net energy is generated, it has been estimated by the developers that tipping fees in excess of $500 per ton may need to be assessed. In addition, the developers have concluded that the cost of acquiring permits would be far higher than originally anticipated (Jones, personal communication). In light of these concerns, the net energy production of the HITECH plant in this report has been scaled down to a moderately optimistic 8 MW of surplus power; if the plant produces any less, the payback period becomes longer than the expected life of the plant.

It is now possible to attempt a benefit/cost analysis of the various options for treating solid waste in Hawai'i, from source reduction to burning MSW for power. Average costs, benefits and payback periods of various options for treating solid waste in Hawai'i and the mainland are listed in Table 1, along with some unmonetized drawbacks for each option. The net avoided greenhouse gas emissions for each method are given qualitatively in Table 2 and quantitatively in Table 3.

These tables are particularly informative in that they account for carbon sequestration in landfills, for carbon sequestration in forests saved from logging by source reduction and recycling, and for emissions from equipment used to transport materials and operate waste management facilities. As can be seen in Table 3, source reduction tends to cause the greatest reduction in emissions, followed in turn by recycling and combustion. Composting is not given its full due in this table, however, since only composting of green waste and food waste are considered (ICF Inc., 1997, p. 8-12).

In summary, it is generally accepted that pre-consumer source reduction is generally the cheapest of the methods discussed above, and also produces much lower greenhouse gas emissions than do the other waste management strategies (Tables 1 and 3). This is generally followed by recycling, both in terms of costs and reduced greenhouse gas emissions (ICF Inc., 1997, p. 8 and 10). An action plan for this sector should concentrate on source reduction first and foremost, both pre-consumer and post-consumer. The results for the other options are more mixed. Composting appears to produce net greenhouse gas emissions which are similar to those of combustion and landfilling, given the uncertainty in the analyses, but tends to have a much shorter rate of return (Table 3).

It thus appears that, before constructing or promoting any new MSW incineration facilities, the counties should carefully consider the costs and benefits of incinerators compared to other methods of disposal. At present, there is no generally-accepted way to account for the full range of benefits derived from reduced greenhouse gas emissions. There have been notable efforts (e.g., Costanza et al. [1997] estimate the global value of tropical forests as regulators of greenhouse gases at $223/ha/yr), but few have been applied to Hawai'i. In spite of this data shortage, those options which appear to provide the greatest reductions in global warming potential for the least cost should nevertheless get prime attention.

Type of Facility	Green Waste Composting Facility		Solid Waste Composting Facility		H-POWER	HITECH
Capacity Net Energy	2,000 T/Yr	60,000 T/Yr	100,000 T/Yr	200,000 T/Yr (W/ Sewage Sludge)	650,000 T/Yr 70 MW	100,000 T/YR 8 MW
Capital Costs	$75,000	$2 Million	$1.5 Million	$45 Million	$181 Million	$52 Million
Operating Costs	$40,000/Yr	$120,000/Yr	$3 Million/Yr	$3 Million/Yr	$54 Million/Yr	$8.5 Million/Yr
Tipping Revenue*	$60,000/Yr	$1.8 Million/Yr	$3 Million/Yr	$6 Million/Yr	$36 Million/Yr	$3 Million/Yr
Product Revenue**	$37,500/Yr	$1.13 Million/Yr	$1.5 Million/Yr	$3 Million/Yr	$27 Million/Yr	$7.7 Million/Yr
Other Benefits	Compost, reduced landfill input.		Compost, reduced landfill input.		Power, reduced landfill input.	Power, materials, reduced landfills.
Drawbacks	Reduces methane-generating capacity of landfills.		Can be fairly high concentrations of heavy metals, etc.		Dioxins; must landfill ash.	Dioxins; periods of downtime likely.
Payback Period	2 Years	1 Year	1 Year	5.5 Years	20 Years	24 Years
W/ Free Compost	4 Years	2 Years	Never	13 Years		

Table 1. Costs and benefits of various solid waste treatment options. From Watson et al., 1996, Section 8.2.1; Jones, 1997; Coxwell Energy, Inc., 1996, p. 11; Hawaiian Earth Products, 1995; Lounsbury & Miller, 1984, p. 61; Tummons, 1997, p. 6. * Based on $30/Ton. ** From Sales of compost or energy. Compost Revenue based on $25/ton for manure and green waste compost, and $20/ton for solid waste compost. Based also on 0.75 tons of compost per ton of original material.

MSW Management Strategy	Manufacturing & Transporting Raw Materials	Changes in Forest Carbon Sequestration	Changes in Soil Carbon Sequestration	Management of Waste
Source Reduction	Decreased emissions due to reduced energy requirements and avoided processing	Increased forest carbon storage	No change	No emissions or sinks
Recycling	Decreased emissions due to reduced energy requirements and avoided processing	Increased forest carbon storage	No change	Transportation and machinery emissions
Composting	No emissions or sinks	No change	Increased soil carbon storage	Transportation and machinery emissions
Incineration	Processing and transportation emissions	No change	No change	CO_2, N_2O and transportation emissions; avoided utility emissions
Landfilling	Processing and transportation emissions	No change	No change	CH_4, machinery & transportation emissions; avoided utility emissions

Table 2. Components of net emissions for various municipal solid waste management strategies. From ICF, Inc., 1997, p. 20.

Material	Source Reduction	Recycling	Composting	Incineration	Landfilling
Newspaper	-480,000	-370,000	NA	400,000	280,000
Office Paper	-530,000	-290,000	NA	460,000	1,090,000
Cardboard	-440,000	-300,000	NA	320,000	440,000
Aluminum Cans	0	-1,010,000	NA	2,970,000	2,970,000
Steel Cans	0	300,000	NA	470,000	880,000
Plastic	0	1,050,000	NA	3,980,000	2,600,000
Food Scraps	0	NA	0	-10,000	90,000
Yard Trimmings	0	NA	0	-20,000	-70,000
Mixed MSW	0	NA	NA	40,000	0
Total	-1,450,000	-620,000	0**	8,610,000	8,280,000

Table 3. Net greenhouse gas emissions from source reduction and various waste management options, assuming the current mix of virgin and recycled inputs into the waste stream. All emissions in tons of carbon equivalent per ton of solid waste (TCE/ton). Both generated and avoided emissions are calculated according to Table 2. Although there is uncertainty in the estimate of greenhouse gas emissions from composting, emissions caused and emissions avoided appear to more or less balance. From ICF, Inc., 1997, p. 115.

4. Reduce Methane Emissions from Landfills (moderate cost, moderate to high benefit)

For the solid waste which does enter landfills—and for the waste which already resides at these sites—a new set of measures is necessary. Landfills produce methane and carbon dioxide in approximately equal amounts. However, methane is a more potent greenhouse gas by both weight and volume than is CO_2. Furthermore, many sources consider most of the CO_2 emitted by landfills to ultimately be taken up by plant growth, and thus they consider net CO_2 emissions to be minor. Nevertheless, in an island state like Hawai'i where most landfill material has been imported, both gases should be of concern.

Anaerobic (oxygen-free) conditions begin to predominate in landfills starting a few months to about two years after they are capped. However, methane generation rates vary both between different landfills and within a single landfill due to differences in water infiltration, depth of landfill, composition of waste, and other considerations (Energy Information Administration, 1995, p. 35). It is thus difficult to estimate costs and benefits of various methods for reducing methane emissions from landfills in Hawai'i.

Some generalizations can be made, however. For example, CO_2-equivalent emissions from landfills without gas collection systems are estimated to be 3 to 5 times higher on average than from landfills with collection systems (IPCC, 1991, p. 116). Currently, Hawai'i has no laws regarding methane emissions from landfills aside from those which mirror federal laws, and it is unlikely that any will be promulgated in the foreseeable future (Harder, personal communication). Aside from reducing the current laxity of this regulatory situation, three separate options for increased reduction of methane from Hawaiian landfills should be taken into consideration by the counties. These involve simply flaring emitted methane, burning that methane for energy, or burning the waste itself for energy.

a. Install Equipment to Vent and Flare Methane

Any landfill containing more than a few thousand tons of MSW can continuously fuel a methane flaring system. A minimum size of 1.1 million tons WIP (with a good lining) is considered necessary to support a methane-to-energy plant, and indeed federal laws (40 CFR 60.33c and 40 CFR 60.752b) now require all current landfills of this or greater size to collect their methane and either flare it or use it to run a generator, for a minimum of 15 years after closure.

At present, however, only four of Hawai'i's public landfills either flare their methane or burn it for power. Both processes require a network of pipes to be drilled into the landfill and then routed to a central collection point, where the gas is collected and either flared or fed into a power generator. While most collection systems are estimated to collect 50% to 70% of the methane and CO_2 emitted, some landfills--such as the Hewitt Landfill in Sun Valley, California--are estimated to capture about 90% of their collectible gas (Schumacher, 1983, p. 245). In Hawai'i, it is estimated that collection from the Kalaheo Landfill also approaches or even exceeds 90%, due to its impermeable cap and negative-pressure collection system. Collection efficiency for the other landfills probably hovers closer to 70%, due mainly to their older (and thus more permeable) caps. At the Pu'u Palailai Landfill on O'ahu, underground fires have been burning continuously since 1988, using up some of the methane generated, yet also reducing the efficiency of the flaring process since the collected gas is high in CO_2 (Harder, personal communication).

For even large landfills (and dumps) closed more than 25-30 years ago, emissions may have already slowed to the point where they are becoming too small to support a methane flare. Some other landfills have never reached a size capable of supporting such a system. But for all others, the primary restraining force at present is simply the lack of a collection system. This will become increasingly the case as smaller landfills consolidate in response to the 1996 EPA regulations. In the long run, it may be in the government's best interest to provide partial subsidization of such collection systems at medium (0.5-1.1 million tons WIP) and large (>1.1 million tons) landfills closed within the last 20 years or scheduled to soon close.

California has recommended, though not required, the installation of gas collection systems at all landfills larger than 0.5 million tons WIP, and has noted that installation at smaller landfills would produce still larger statewide emission reductions (California Energy Commission, 1991, p. 5-85). Nationwide, collection and flaring for a 1 million tons WIP landfill requires an average of about $630,000, and operating costs average around $150,000 per year (Watson et al., 1996, Section 8.2.2). In Hawai'i, methane collection and flaring is typically paid for by the counties (Baker, personal communication).

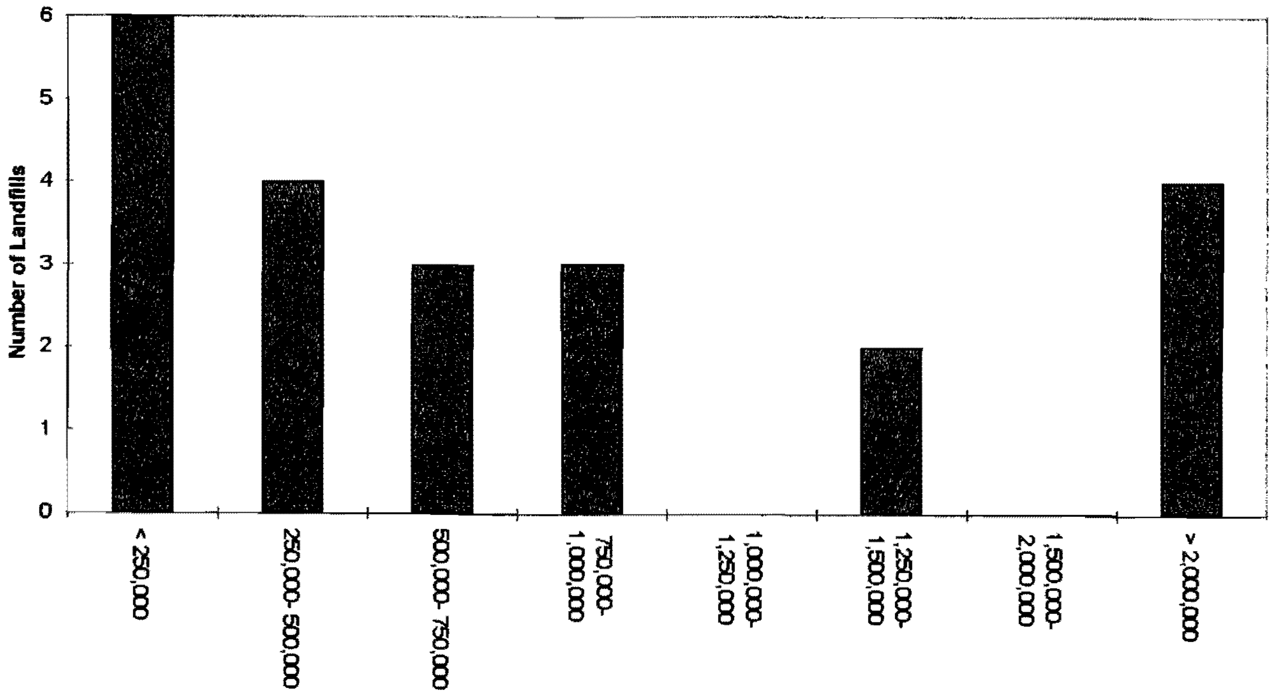
b. Install Equipment to Refine, Transport or Burn Methane for Energy

It is generally agreed that, with current technology, it is not economically feasible to burn methane from any landfill smaller than 500,000 tons WIP and less than 30 feet deep for energy generation, and nearly all such systems operate at landfills significantly larger than 1 million tons WIP (State of Hawai'i, 1984, p. 54-55; Campbell, 1989, p. 399). However, at least one landfill as small as 413,000 tons WIP (in Denmark) has managed to pay for its methane-burning system within 13 years (see below). In Hawai'i, the majority of both operating and closed landfills are smaller than 1 million tons WIP, and many are smaller than 500,000 tons (Figure 12). Thus, methane combustion for energy is a strong option at only four or five landfills in the state, and a possible option for perhaps six or seven more.

Methane emissions from landfills will be reduced significantly as the counties conform to the source performance standards promulgated by the EPA in March 1996. These standards require capturing or flaring of gas from operative landfills which (a) have greater than 2.75 million tons of design capacity, (b) accepted waste after November 1987, and (c) have *non-methane* organic compound emissions of greater than 50 tons per year. Such landfills must comply by the year 2000. The EPA also recommends that any landfill with greater than one million tons WIP which is open or recently closed should also consider converting methane to energy (EPA, 1996a, p. 4-5). Hawai'i has seven landfills which appear to fit these criteria; however, in 1997 only two were burning methane for power and heat generation, and one simply flared its methane (Table 4). If all seven had captured 75% of their methane emissions in 1996, approximately 14,700 tons of avoided methane emissions would have resulted (Table 4), equal to approximately 135,000 barrels of oil or 0.85 MW of energy. The avoided tonnage would increase further if all seven had burned this methane for power and/or heat.

Economic feasibility of methane utilization from landfills depends on (a) volume and depth of the landfill, (b) composition of refuse, and (c) rate of water infiltration. If the gas is to be sold, other considerations include (d) potential buyers in the local area, (e) cost of upgrading methane to acceptable purity, (f) the going price of such natural gas, (g) regulatory restrictions, (h) the availability of tax incentives and subsidies, and (i) the anticipated social, political and technical obstacles (EMCON Associates, 1980, p. 111). The useful life of methane gas generation is generally about 20 years in dry climates, and often less in moist climates (Ham and Barlaz, 1989, p. 164). Over this period, the volume of methane and CO_2 emitted is generally in the range of 120-300 yd^3/ton dry waste (Ham and Barlaz, 1989, p. 165).

Figure 12. Size Classifications of Landfills in Hawaii



Landfill Name	Class	Acres	Years of Operation	Municipal Solid Waste (MSW) Landfilled per Year (tons)	30-Year Growth Correction Factor (percent)	Volume of MSW in Place (MSWIP) (yd^3; in bold if quoted)#	Weight of MSWIP (tons; in bold if quoted)*	Is Landfill Large or Small?	Methane Emissions (tons/year)****
Hawaii County									
Hilo Landfill	Nonarid		1970s-Present	**56,314**	67.2		756,860	S	1,734
Puu Anahulu & Kailua LFs	Nonarid	20+18	1970s-Present	**62,571**	51.4		643,735	S	1,475
Maui County									
Central Landfill	Arid		1970-Present	**152,833**	58.2	3,226	**2,312,674**	L	5,648
Hana Landfill	Nonarid		1965-Present	**1,251**	60.3		19,620	S	45
Olowalu & Makani LFs		2 x 15?	Closed in late 1980s		58.2	726,000	435,600	S	998
Lana'i Landfill	Arid		1975-Present	**2,190**	75.4	86,691**	34,676	S	79
Kalama'ula Landfill	Arid	19	Early '70s-1993			**326,500**	195,900	S	449
New Moloka'i Landfill	Arid	20	1993-Present	**4,693**	89.2	54,750	12,558	S	29
Honolulu County									
Kapa'a LF (6 Parts), Kailua	Nonarid	133	1960s-Present	xxx	xxx	xxx	xxx	xxx	xxx
Central Site	"	33#	1970-1979		82.1	**4,166,667**	**2,500,000**	L	5,727
Site No. 2	"	34	1982-1997	141,333	82.1	**3,540,000**	**2,122,147**	L	1,090
Site No. 3	"	16	1979-1982		82.1	**1,000,000**	600,000	S	3,855
Two Old Landfills	"	40#	1950s-1970s		82.1	580,800	348,480	S	798
One Old Constr. LF***	"	10#	1950s-1970s		82.1	145,200	145,200	S	333
Kalaheo LF, Kaneohe	Nonarid		1987-1990		82.1	2,183,333	**1,310,000**	L	4,598
Waimanalo Gulch Landfill	Nonarid		1989-Present	300,000	82.1	**3,500,000**	600,000	S	3,855
Kawailoa LF, Waialua	Nonarid	28#	1960s-1986		82.1	1,761,760	1,057,056	S	2,421
Puu Palailai LF, Makakilo	Arid	29	1974-1988		74.5	4,600,000	2,800,000	L	6,158
Wai'anae Landfill	Arid	20	1971-1984		74.5	774,400	**1,400,000**	L	4,692
Nanakuli Constr. LF***	Arid?		1990-Present	200,000	82.1	**200,000**	200,000	S	458
Kauai County									
Kekaha Phase I Landfill	Nonarid		1953-1995	62,571	69.0	**763,886**	458,332	S	1,050
Kekaha Phase II Landfill	Nonarid	36	1993-1997	65,700	69.0	**496,668**	298,001	S	683
Halehaka Landfill	Nonarid		1970s-1995		69.0	363,000	217,800	S	100
Total Landfill	Regular Plus C & D MSW (tons/yr):			**986,887**		MSWIP Total (tons):	**17,615,213**		**46,274**
Waipahu Incinerator	*(Arid)*	*xxx*	*1967-1994*	*187,714*	*0*	*187,714*	*5,068,286*	*(L)*	*8,534*
H-Power Plant	*(Arid)*	*xxx*	*1990-Present*	*600,000*	*0*	*600,000*	*4,120,398*	*(L)*	*7,541*
Recycling (Oahu)			*1980-Present*	*332,000*	*0*	*332,000*	*2,475,000*	*(L)*	*5,818*
Total Avoided Landfill	Waste Kept Out of Landfills (tons/yr):			***1,119,714***			*Total Avoided MSW (tons)*		***21,893***

Table 4: Waste in place and methane emissions by landfill for Hawaii. Data from various sources.

*except where noted, sites are compacted; assumes 0.6 tons per cubic yard

**not compacted; assumes 0.4 tons per cubic yard

% of WIP in Large Landfills: 59.9%

***construction landfills assume 1 ton per cubic yard

****for Kapaa and Halehaka landfills, flaring assumes 80% efficiency.

#volumes are estimates based on 4840 yd^2/acre. If depths are unknown, landfills are assumed 3 yds deep if operating < 10 yrs, 7 yds deep if operating 10-15 y and 10 yds deep if operating >15 yrs

EPA formula for large landfill emissions = (419,000 + CCF * methane-producing WIP) * 0.0077; CCF = climate correction factor (0.16 if arid, 0.26 if nonarid)

There are three broad uses for landfill methane. In order of increasing cost, these are: (1) sale of unrefined, low-kilojoule gas to nearby industrial customers; (2) onsite use of this low-kilojoule gas for electrical generation or heating; (3) refinement into methanol (methyl alcohol) or pipeline standard gas (essentially pure methane) for injection into nearby utility company pipelines; or (4) generation of electricity onsite and sale to utility grid (EMCON Associates, 1980, p. 111-112). Options 1 and 2 may both require only that the gas be passed through a condensate collector and then compressed, as long as the resulting gas is not so corrosive that it damages existing pipelines, boilers and furnaces (EMCON Associates, 1980, p. 112; State of Hawai'i, 1984, p. 65). Utilities in Hawai'i lso tend to lack equipment capable of making use of landfill gas unless it has been fully refined into standard pipeline gas (Harder, personal communication).

On the other hand, it is doubtful whether any landfills in Hawai'i aside from Kapa'a/Kalaheo and Waimanalo Landfills on O'ahu and the Central Maui Landfill generate sufficient methane to justify option 3, especially since 30% to 40% of the heating value of the gas is used or lost in the upgrading process (State of Hawai'i, 1984, p. 66). Only one facility has attempted either option 3 or 4. Since 1989, Kapa'a Energy Partners have operated a turbine to burn methane from Kapa'a and Kalaheo Landfills for generation of electricity, which is then sold to the island's electric utility. Peak production has been 2.9 MW. This plant then pipes its exhaust heat to the nearby Ameron Quarry, where it is used to dry aggregate (Greer, 1997, p. 16; *Honolulu Advertiser*, May 26, 1997, p. A22). Unfortunately, although the heat is bought at a price based on the diesel fuel oil saved by the quarry, estimates of the fuel thus saved are unavailable, hindering any benefit/cost analysis (Greer, 1997, p. 16).

A similar option may be possible for the Central Maui Landfill, since it also sits beside an Ameron quarry (Harder, personal communication). However, this option is hindered by the low percentage of methane in the landfill's gas and the high percentage of hydrogen sulfide (H_2S) generated by the biosolids (sewage sludge) deposited there over the years (Baker, personal communication).

Options for refining gas into natural gas or methanol and bottling or piping it offsite are also quite limited. The state considers these options to be economically infeasible anywhere, in spite of the fact that such an operation would have no additional permitting requirements aside from the standard building permits. Furthermore, methanol is a poisonous substance which can be dangerous when proper safety precautions are not followed (Harder, personal communication).

A brief look at some methane-to-energy projects elsewhere provides some insight. Of particular interest is a pilot project conducted in Denmark in the 1980s. This project transferred untreated gas from a 413,000 ton landfill to a district heating station, generating 35 kW of energy and paying for itself within 13 years (Willumsen and Burian-Hansen, 1986, p. 125, 127 and 128). One landfill in England (size unspecified) paid for its 750 kW generation system in just 3.2 years when the "benefits of gas control" were included, and 4.7 years when these benefits were left out. However, the British study cautioned that this payback occurred with the help of a government subsidy, and that even then any exportation of methane via pipelines became uneconomical once those pipelines exceeded a mile or so in length (Bevan and Aitchison, 1991, p. 16-19).

On the other hand, the California Energy Commission has concluded that upgrading landfill gas to pipeline quality in that state is the only option in which the economic benefits exceed costs even for a landfill with 7 million tons WIP. Even moderate refining and sale to industrial customers was necessary just to break even (Table 5). However, this analysis did not consider burning of low-kilojoule gas onsite for power production (California Energy Commission, 1991, p. 5-90). It also appears to contradict the profitability of the Ascon Landfill in Wilmington, California, which collects gas from its 1.8 million tons of WIP, then sells most of its unrefined gas to a nearby Shell Oil refinery to be used as a supplementary fuel (Schumacher, 1983, p. 88).

In regard to the profitability of methane-to-energy plants, different authors appear to view the same data differently. According to one author (Watson et al., 1996, Section 8.2.2), methane-to-energy plants at landfills tend to cost about $1,000 to $1,300 per net kW, with electric generation costs ranging between four and seven cents per kWh if no collection infrastructure was previously in place. Since this is the same range of income per kWh the facility could expect, the payback period is likely to be long if not infinite. The EPA, however, notes that a small change in energy prices can put a plant well into the black. Table 6 shows payback periods varying considerably by simply changing the price of energy from $0.05/kWh to $0.06/kWh. This is due to economics of methane recovery: At $0.06/kWh, it is potentially profitable to collect 65% to 75% of landfill emissions; at $0.05/kWh, this drops to 50% to 60% of emissions, and at $0.04/kWh a mere 10% to 15% can be economically collected (EPA, 1993b, p. 4-2).

Measure	Private Cost, $	Private Benefit, $	Emissions Benefit, $	Total Benefit, $	Benefit/ Cost	Production/Reduction Estimate of CO_2 Equivalent Emissions Over a 23-Year Time Scale
Business as Usual Size = 1 Million MSW tons in place	0	0	678,000			Produce=2.5 million tons
Collect and Flare Size = 1 Million tons MSW in place Gas Recovery = 1 Million scf/day	2,000,000	0	-2,280,000	-2,280,000	-1.14	Production=1.54 mill tons Reduction=0.96 mill tons
Medium Btu and Sell for Combustion Size = 7 Million tons MSW in place Gas Recovery = 5 Million scf/day at 550/Btu/scf	8,830,000	16,070,000	-11,410,000	4,660,000	0.53	Production=9.8 mill tons Reduction=7.7 mill tons
High Btu and Sell Size = 7 Million tons MSW in place Gas Recovery = 3 MM scf/day at 1000 Btu/scf	13,260,000	72,400,000	-2,140,000	70,260,000	5.30	Production=8.75 mill tons Reduction=8.75 mill tons

Table 5. Comparison of modeled landfill gas mitigation options in California. Covers a 15-year period and assumes a constant prices for electricity of $0.0749/kWh. Medium BTU gas price = $2.25/MM BTU; high BTU gas price = $4.41/MM BTU. From California Energy Commission, 1991, Table 5-24.

a. Assuming $0.06/kWh and 70% recovery

Landfill Size (tons)	Methane Recovered (tons/yr)	Methane Emitted (tons/yr)	Generator Capacity (MW)	Cost (dollars)		Annual Revenue (dollars)	Payback Period (years)
				Capital	Annual O&M		
137,817	529	199	0.3	597,000	96,000	124,830	20.7
275,634	1,015	397	0.6	1,060,000	137,000	239,760	10.3
551,268	3,704	1,446	1.1	1,927,000	219,000	874,800	2.9
2,756,340	9,465	3,711	5.2	8,055,000	806,000	2,235,600	5.6
5,512,679	16,708	6,533	9.1	14,109,000	1,379,000	3,946,320	5.5

b. Assuming $0.05/kWh and 55% recovery

Landfill Size (tons)	Methane Recovered (tons/yr)	Methane Emitted (tons/yr)	Generator Capacity (MW)	Cost (dollars)		Annual Revenue (dollars)	Payback Period (years)
				Capital	Annual O&M		
137,817	415	298	0.3	597,000	96,000	81,734	Never
275,634	798	596	0.6	1,060,000	137,000	156,986	53.0
551,268	2,910	2,170	1.1	1,927,000	219,000	572,786	5.5
2,756,340	7,437	5,567	5.2	8,055,000	806,000	1,463,786	12.3
5,512,679	13,128	9,799	9.1	14,109,000	1,379,000	2,583,900	11.7

Table 6. Costs, benefits and payback periods for representative landfills in the US. Does not include permitting costs or revenue from heat. Cost includes collection, flaring (for excess gas) and generator systems. Assumes 1,000 BTU/f and 12,000 BTU/kWh. From EPA, 1993, pp. 4-2, 4-27 and 4-28.

Interestingly, the study above suggests that landfills on the order of 0.5 million tons WIP may actually have the shortest payback period. While this ignores the costs of acquiring permits and land (nor does it account for the higher costs of labor and materials in Hawai'i), it also ignores the revenue from heat generated. Furthermore, the EPA has placed a dollar figure on the value of each ton of carbon emissions avoided by alternative energy sources. These added benefits are estimated to amount to between $5 and $20 per ton of carbon avoided, or $0.007 to $0.028 per kWh (EPA, 1993, p. 4-5). Thus, the results of this study should be considered carefully by state and county governments.

Of course, the economics of flaring vs. burning methane for energy need to consider the relative reductions in global warming potential (GWP). Flaring of one cubic foot of typical landfill gas results in an approximate 53% reduction in the GWP of that gas, while burning in a combustion device results in an approximate 65% reduction in GWP. Refining the gas to pipeline quality results in an approximate 77% reduction in GWP (California Energy Commission, 1991, p. 5-86). This equipment itself produces greenhouse gases such as NO_x and CO, as well as hydrocarbons which react with air to form ozone (California Energy Commission, 1991, p. 5-87). Table 5, shown earlier, summarizes these emissions from the various methane mitigation devices as calculated by the California Energy Commission.

In addition to reduction of greenhouse emissions, the benefits of landfill gas collection include:

- Reduction of odor and explosive hazard in the vicinity of the landfill, and thus increased land use potential;

- Reduction in emissions of other air pollutants such as hydrocarbons (Schumacher, 1983, p. 303);

- Reduction in generation of leachate, since entrained water vapor condenses in collection pipes and is removed periodically (EPA, 1993b, p. 4-15);

- Since methane is poisonous to plants growing on the landfill cap, gas collection can improve the quality of grasses used to reduce erosion of the soil cap;

- If the methane is sold or burned for energy, the landfill or its customer may reduce energy costs, and the state as a whole will see a marginal reduction in its dependency on imported fossil fuels as well as the creation of a certain number of jobs. Selling methane as natural gas is often cheaper than burning it onsite for energy.

There are tradeoffs to this approach, however:

- Collection pipes must be carefully placed and angled so as to minimize damage from settling of landfill material, as well as ponding of liquid which can clog pipes (Stegmann, 1989, p. 171);

- Internal combustion engines tend to be cheaper to operate than gas turbines, thus negating much of the desirability of this energy source even for the landfill itself. Engines can be altered to accept landfill gas as a fuel, but this raises costs;

- Collection for power generation can only be cost-effective at large landfills;

- Enhancing methane production can require infiltration of rainwater, which in turn can increase leachate percolation into groundwater. Waste in place should have at least a 50% moisture content for optimal methane generation (State of Hawai'i, 1984, p. 64). On the other hand, if the landfill is designed to contain its leachate, controlled addition of water can actually quicken the attenuation of toxic substances within the landfill (Schumacher, 1983, p. 269-273);

- Generation rates are also reduced when green waste, food waste and biosolids are redirected to composting or other operations, since these wastes produce the most methane per ton of dry waste. As Figure 13 shows, these are the first wastes to break down in a landfill, and thus can provide extra power during the first few years of plant operation when emissions from more refractory wastes such as paper are still low (Schumacher, 1983, p. 132-137). However, as noted above,

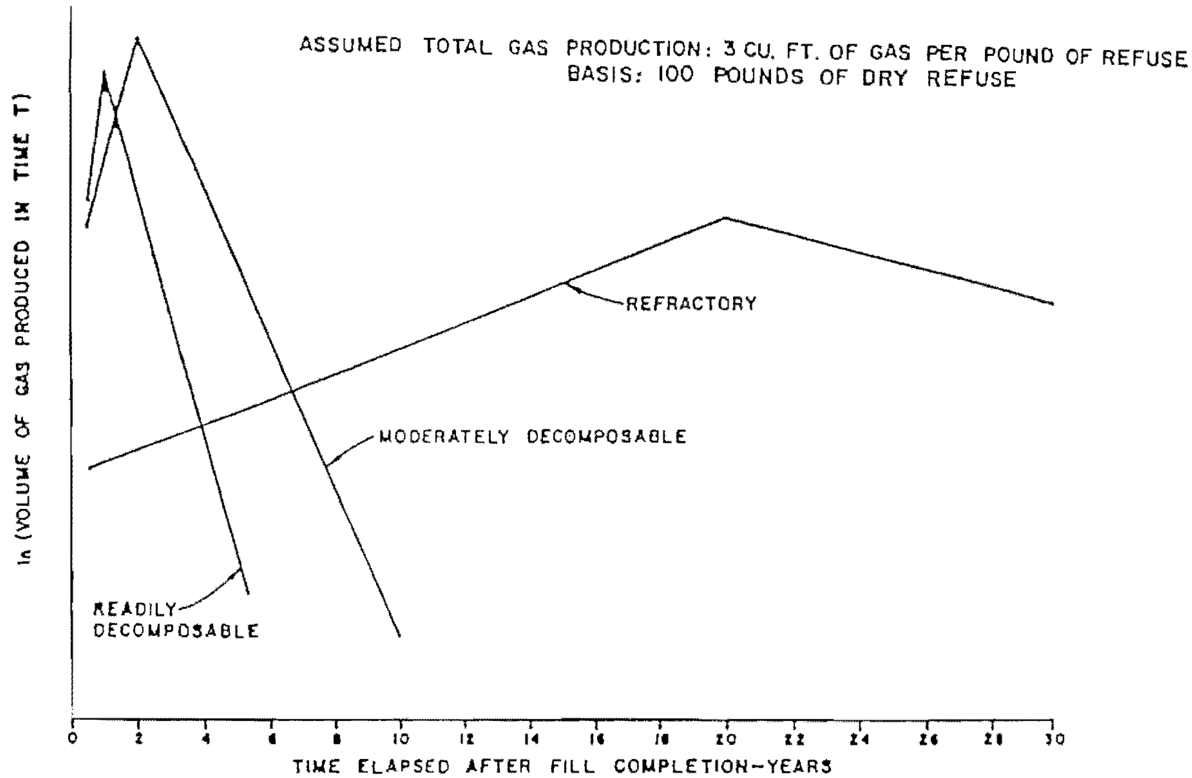


Figure 13. Typical modeled rate of gas production from different categories of solid waste. From Schumacher, 1983, p. 133.

biosolids also emit corrosive hydrogen sulfide gas (Baker, personal communication), so diversion of biosolids is a mixed blessing;

- It may be necessary to have one collection system for gas recovery and another to prevent migration of gas beyond the landfill boundary (California Energy Commission, 1991, p. 5-84);

- Condensate can itself contain harmful substances, and if it is not feasible to return it to the landfill, disposal problems can result (Schumacher, 1983, p. 304);

- Recovery equipment itself can emit greenhouse gases such as CO_2 and NO_x;

- If the landfill is near a populated area, noise from plant operations or light from flares can cause public relations problems (Schumacher, 1983, p. 304);

- In some places, zoning or permitting requirements may complicate matters. In California, for example, permits, which take up to a year to be granted, are required if a landfill sells its methane offsite, but not if it generates gas solely for its own use (Schumacher, 1983, p. 308).

As of 1996, the EPA requires many landfill owners and operators to collect and, at the very least, flare their landfill gas. Many states also require collection and flaring of this gas (EPA, 1995a, p. 5-39). Energy recovery projects for landfill gas in the U.S. are also aided by an "unconventional gas" tax credit worth approximately one cent per kWh (Watson et al., 1996, Section 8.3.3).

In Germany, laws require public utility companies to accept landfill gas utilization for energy production (Stegmann, 1989, p. 179). However, other regulations can get in the way of such transfers. For example, one landfill operator in southern California was required to install catalytic converters on its gas compressors in order to comply with NO_x standards (Schumacher, 1983, p. 55). Fortunately, emissions of both NO_x and CO from burning of unrefined landfill gas are generally significantly lower than those for natural gas under the same conditions (Schumacher, 1983, p. 56), something which should be taken into account during the permitting process.

In California, the Integrated Waste Management Act of 1989 has prioritized that state's options as follows: (1) source reduction, (2) recycling and composting, and (3) waste-to-energy plants. This is the preferred order of methods to be considered for the Act's main purpose: Diverting 50% of the state's waste stream from landfills by the year 2000 (California Energy Commission, 1991, p. 5-89). Recommended incentives to help accomplish this goal include: (a) a municipal solid waste sorting program, (b) education of consumers and industrial producers of recycling and composting options, (c) increasing solid waste tipping fees at landfills, and (d) research to determine the optimal mix of recycling and composting (California Energy Commission, 1991, p. 5-101).

For gas emanating from existing landfills, the California Energy Commission has recommended three separate options: (a) making its current recommendation regarding collection of methane at landfills larger than 0.5 million tons WIP mandatory; (b) tightening the state's air quality regulations to further encourage such collection; and (c) implementing a program for upgrading landfill gas to pipeline quality through loans, tax breaks and subsidies (California Energy Commission, 1991, p. 5-100).

In Hawai'i, state and county governments can aid methane recovery and utilization from landfills in several ways. One obvious method is through monetary incentives in addition to the federal government's one cent per kWh "unconventional gas" tax credit. Other methods may be more cost-effective in the long run, however. For example, educational seminars and reports can serve to inform landfill operators of new technology for gas collection which may tip the balance of recovery ventures into the black.

c. *Enforce Federal Rules and Recommendations and Promulgate Laws Reducing Methane Emissions From Landfills Which Are More Stringent Than Federal Laws.*

- Implement the source performance standards recommended by the EPA in March 1996 (U.S. EPA, 1996a), and enforce the new EPA rules regarding methane recovery (noted above in Section 4b).

- Require public utility companies to accept landfill gas utilization for energy production, and streamline the permitting process for landfills which choose to sell their methane offsite.

- Tighten the state's air quality regulations to further encourage such collection, yet allow some leeway for such alternative power generator systems which otherwise reduce greenhouse gas emissions.

One regulatory option would apply the concept of pollutant allowance trading which has recently been applied to wastewater in Colorado and North Carolina. In these states, pollutants such as nitrogen and phosphorus were capped at a maximum emission level for the states' wastewater treatment plants (WWTPs), together with—in North Carolina—an industrial firm. These companies then had to decide among themselves how to allot the effluent allowances (National Institute for Water Resources, 1996, throughout). A similar program could be applied to landfills in Hawai'i, as well as to WWTPs and possibly to feedlots. This would be complicated by the fact that most of Hawai'i's landfills and WWTPs are county-owned, however. As a result of the legal and technical uncertainties, this possibility will not be considered further in this report.

d. Avoid deprivatizing landfills.

One potential impediment to the initiation of methane recovery and utilization systems stems from the fact that the Hawai'i state government has recently begun requiring privatized landfills (which make up most of the state's landfills) to be turned over to the government, in spite of the higher costs of operation which this transfer entails (*Honolulu Advertiser*, June 8, 1997, p. A27). Such deprivatization could slow down upgrades, since "given their numerous responsibilities, some municipalities may be unable to place a high priority on developing a landfill methane power project" (EPA, 1993a, p. 4-33). State officials also note that counties may lack both the capital and the expertise to deal with federal regulations regarding landfills, such as Federal Rule 91 (Harder, personal communication). However, this seems unlikely in Hawai'i. Using diversion of material from landfills as a proxy, the county in Hawai'i with the highest percentage of county-run landfills at present (Maui, where both landfills are county-run) is also the county with the most ambitious diversion program. Thus, it appears that deprivatization will make little or no difference in terms of methane collection (Baker, personal communication; Tanegawa, personal communication).

B. Livestock and Manure Management

For the U.S. as a whole, methane emissions from agricultural sources totaled nearly one third of all anthropogenic methane emissions in the early 1990s, and livestock emissions have been increasing by about 1% per year. Some 94% of these emissions are from livestock management, resulting from enteric fermentation in digestive tracts (63%) and the decomposition of animal waste (31%). Burning of crop residues comprises much of the remainder (Energy Information Administration, 1995, p. 37).

Methane emissions from enteric fermentation sources are increasing across the U.S. by about 2% per year, due mainly to increases in beef cattle populations but also to increased animal sizes and productivity (Energy Information Administration, 1995, p. 37-38). Methane production from enteric fermentation is greatest among ruminant animals, including cattle, sheep and goats. These animals possess a rumen, or forestomach, that allows them to digest large quantities of cellulose found in plant material via microorganisms present in the rumen. Other animals, such as swine and horses, also emit methane, but at much smaller rates than do ruminants.

Methane production from livestock digestion is a function of several variables, including quality and quantity of feed intake, the growth rate of the animal, its productivity (reproduction and/or lactation), and its mobility (Energy Information Administration, 1995, p. 38-39). As with methane emissions from enteric fermentation, over half (57%) of all emissions from manure management in Hawai'i are from cattle, with chickens and pigs making up much of the rest (see Table 9). As an extreme example of the volume of manure potentially involved, Hawai'i's principal feedlot (now closed), a 14,000-head lot at Campbell

Industrial Park on O'ahu, accumulated a 150,000 ton mountain of manure over a 10-year period in the 1970s and early 1980s (Dugan and Takahashi, 1985, p. 5).

Although some information is proprietary, it is known that the largest cattle operation in Hawai'i today is a 21,000-head calf-breeding (or cow/calf) ranch at Parker Ranch in the north of the Big Island. Approximately 800 more cow/calf farms are operating, most of which have fewer than 200 head (and many of which have fewer than five head). Nearly all calves are sent to the mainland to fatten on pasture there, totaling about 40,000 per year (Rauson, personal communication). Only one feedlot (consisting of a few hundred head) continues to operate. This feedlot, on Maui, slaughters cattle on-island. The largest hog farm has about 300 head, while most of the 350 or so others have fewer than 60 head (Zaleski, personal communication; Moniz, personal communication).

Manure emissions vary as a function of the amount of decomposable organic matter in the manure, and by the way the manure is managed. The former varies according to diet: The greater the digestibility of the feed, the greater the methane-producing potential of the manure (EPA, 1995c, p. 61). The latter varies according to animal type, with all but beef cattle being mainly kept in pens or cages. As a result, most agriculture operations--in Hawai'i and elsewhere--utilize liquid-based waste management systems which operate predominantly under anaerobic conditions (Energy Information Administration, 1995, p. 40-41). Since liquid slurries lend themselves much more readily to anaerobic digestion than to aerobic composting (EPA, 1993b, p. 6-22), anaerobic treatment has been prioritized in the discussion below.

As for state support options, there is little to go on in terms of mainland examples. As of at least 1991, the U.S. Office of Technology Assessment (OTA) was unaware of any states with agricultural programs specifically designed to reduce greenhouse gas emissions (OTA, 1991, p. 330).

It is imperative to note that the following recommendations necessitate a joint effort between governmental policy change and onsite management improvement to be effective. As mentioned previously, when these two approaches operate in tandem, they can accomplish significantly more than could either approach alone. These actions can be encouraged, for example, by government loans, tax breaks, and educational workshops.

1. Recover Methane from Stored Manure (moderate to high cost, moderate benefit)

It is estimated that about 50% to 90% of the methane which is currently generated from animal waste worldwide can be recovered and used for energy instead of being vented to the atmosphere (OTA, 1991, p. 255). A technique called anaerobic digestion (also known as anaerobic fermentation) can be used to maximize methane generation from livestock waste within a controlled, oxygen-free environment. The gas produced is called biogas (generally about 60-70% methane and 30-40% carbon dioxide) and can be used as a substitute for natural gas or combusted for electricity generation (California Energy Commission, 1991, p. 5-104; Hobson and Wheatley, 1993, p. 240). While combustion converts methane into CO_2, creating approximately the same amounts of CO_2 that aerobic process would have produced, this burning replaces the fossil fuels which would have been used in its stead. The gas emitted by anaerobic digestion is compared to the products of simple anaerobic ponds and aerobic lagoons in Table 7.

	Aerobic Spreading	Anaerobic Lagoon	Anaerobic Digester
CH_4	< 1%	60%	> 60%
CO_2	> 85%	< 5%	30%
H_2	< 5%	5% to 10%	5%
N_2	< 10%	20% to 30%	< 5%

Table 7. Gas compositions produced by various animal waste treatment technologies on the mainland. From Dugan and Takahashi, 1985, p. 22; Joblin, 1996, p. 439.

In China and India, millions of anaerobic digesters, averaging about 30 cubic feet in size, have been in use for many years for production of biogas and fertilizer on small farms. Even as few as 7 or 8 cattle can be sufficient to produce enough gas for one family's cooking and lighting needs in these countries, while supplying fertilizer to fields and fishponds (Figure 14). Unfortunately, these digesters, while cheap to construct and maintain, tend to be labor-intensive (Hobson and Wheatley, 1993, p. 186-188 and 240). Another concern in the U.S. is the common addition of antibiotics to livestock feed-antibiotics which can also kill anaerobic bacteria (Heduit et al., 1986, p. 92).

Methane recovery potential from manure depends on many factors, including equipment design and livestock type (Table 8), and has only proven cost-effective in the U.S. for larger livestock operations. Unfortunately, these are generally not representative of livestock operations in Hawai'i.

Type of Waste	Typical Gas Yield per Metric Ton of Volatile Matter Fed to Digester (m^3)
Sewage Sludge	400-450
Pig Slurry	450
Cattle Slurry	200-400

Table 8. Typical gas yields from sewage sludges and farm slurries in the EEC (Bruce, 1988, p. 188).

In spite of these drawbacks, as early as 1992 at least 23 projects were recovering methane from dairy, swine, poultry and goat manure nationwide. The average U.S. manure

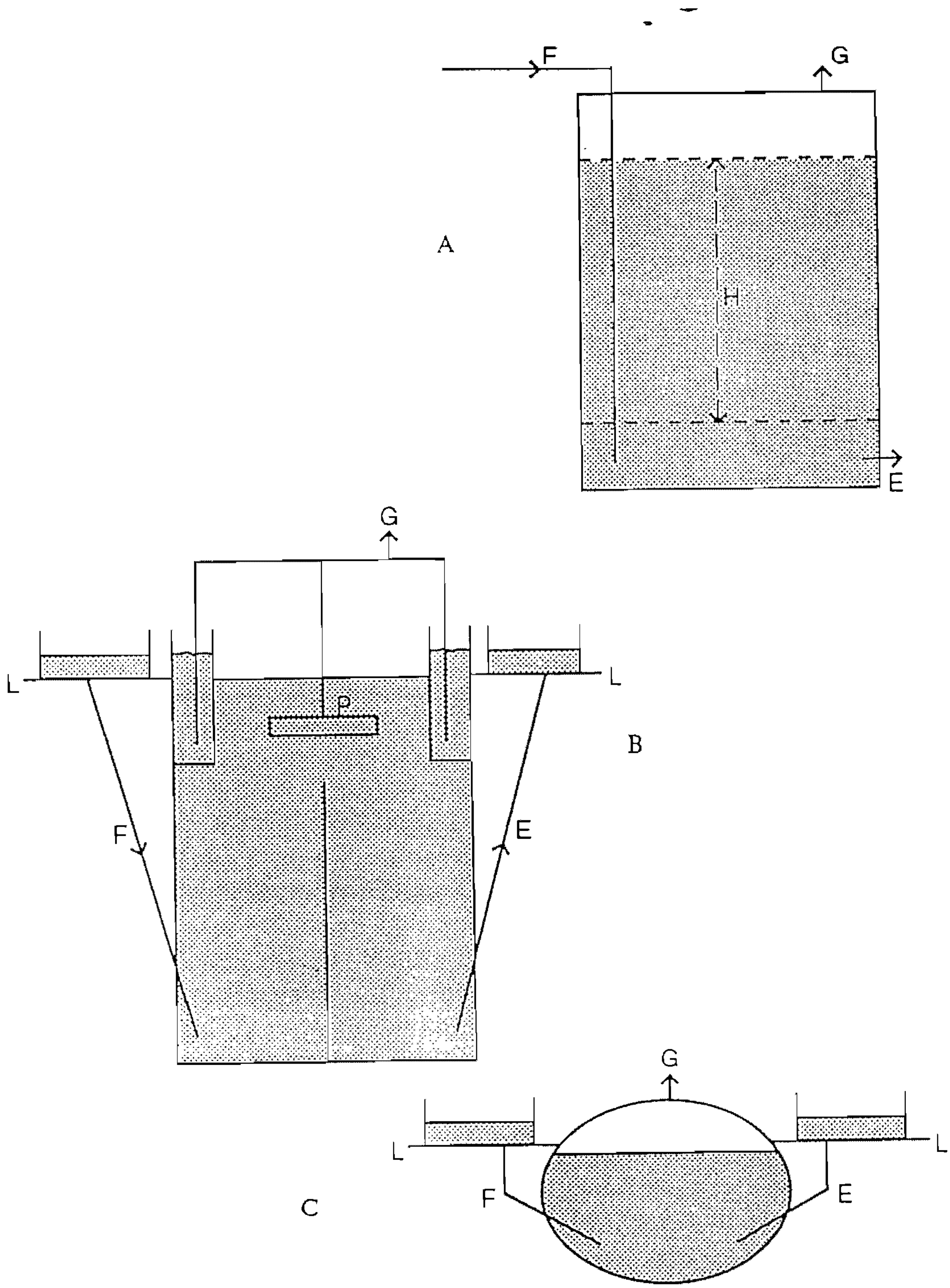


Figure 14. Diagrams of some common digester systems for small farms. A = fed-batch digester. This digester is gradually filled up over the depth H and then emptied, retaining the sludge below H as inoculum for the next filling. B = Indian Gobar digester with floating gas holder. The lower dividing wall is optional. C = Chinese concrete digester. F = feed inlet; probably pumped for A, but gravity fall from collecting tanks in B and C. E = effluent. G = gas flow. P = paddle stirrer attached to gas holder top. L = ground level. From Hobson and Wheatley, 1993, p. 187.

digesters for cattle, swine and chickens were served by around 600, 3,300 and 200,000 head, respectively (EPA, 1993a, p. 6-16; Table 9). These populations are significantly larger than the typical livestock operation in Hawai'i, but—as will be discussed below—a cluster of operations could muster the necessary populations. While benefit-cost data for mainland operations have not been found, one would expect that at least some of these operations (especially the larger ones) must be cost-effective in order to drive the market for their construction.

Animal Type	Number of Digesters in Use Nationwide in 1990	Average Livestock Population Serving Each Digester in U.S. (head)	Head in Hawai'i in 1994	Number of Farms in Hawai'i in 1994	Estimated No. of Digesters Hawai'i Could Support	Methane Production in Hawai'i in 1990 (tons)	Estimated CH_4 Production in Hawai'i Using Digesters at Farms of at Least Moderate Size
Cattle	15	600	16,112	900	2	3,244	650
Swine	5	6,600	35,000	350	2	1,101	400
Chickens (Layers)	2	200,000	823,000	55	2	1,400	400
Total	22			1,305	6	5,745	1,450

Table 9. Average sizes of US feedlots fueling anaerobic manure digesters in 1992, compared with livestock populations in Hawai'i as of 1994. From US EPA (1993), p. 6-16 and Hawai'i Agricultural Statistics Service, 1995.

The six digesters listed as possible for Hawai'i in the table above could be further consolidated if they not only fed neighboring farms with the same livestock, e.g. cattle farms, but also neighboring farms whose livestock types differ from those of their neighbors; e.g., cattle farms and hog farms.

For Hawai'i, the following recommendations should be carried out where feasible.

a. *For the largest farms, evaluate pros and cons of a system which would combine anaerobic digestion, burning of the methane for power and photosynthetic reclamation of the remainder.*

One interesting option which has been considered for Hawai'i involves supplementing a methane-to-energy animal waste treatment plant with cultivation of some crop, such as algae, which utilizes the remaining nutrients. For example, Dugan and Takahashi (1985) estimated the costs of a 60-acre plant to treat the waste slurry from a 10,000 head beef feedlot operation which combined anaerobic digestion, burning of the methane for power and photosynthetic reclamation of the remainder. These authors concluded that the construction and maintenance costs would total approximately $1 million in 1985 dollars, with the biogas and algae each bringing a profit of $500,000 per year. As a result, they estimated a 5-year payback period even without including the benefits of reduced waste shipping costs (Dugan and Takahashi, 1985, p. 52-53).

A similar operation is currently being carried out at Keahole Point on the Big Island, where the Cyanotech company raises Spirulina algae on nutrients brought to the surface by the OTEC power plant. This company has been highly successful (*Honolulu Advertiser*, July 9, 1996, p. A3), but it is difficult to say whether another plant would be as successful or whether it would oversaturate the market.

b. *Place covers on liquid waste lagoons at individual farms, and treat solid manure with plug flow or mixed tank digesters. Flare the methane or use it to generate electricity and heating for farming uses.*

This approach to recover methane has rarely been used in Hawai'i. The primary reasons are the relatively small size of Hawai'i's farms and the lack of a thorough economic study on the potential costs and benefits for local livestock operations (Paquin, personal communication). This option is widespread elsewhere in the U.S., however, and could prospectively be valuable in terms of both sustainable energy use and the mitigation of methane emissions into the atmosphere.

A cost-benefit analysis of several mainland livestock methane-to-energy projects is summarized in Table 10.

Recovery System	Farm Size (head)	Cost (dollars) Capital	Cost (dollars) Annual O&M	Annual Benefit (dollars)	Payback Period (years)
Dairy Farms					
Covered Lagoon	250	69,500	2,100	10,600	7.0
Complete Mix	250	117,400	1,500	8,600	11.7
Plug Flow	250	97,800	1,100	6,200	10.3
Covered Lagoon	500	99,800	4,200	21,300	8.2
Complete Mix	500	168,200	3,100	17,100	15.2
Plug Flow	500	130,100	2,200	12,500	12.3
Covered Lagoon	1,000	163,800	8,500	42,600	11.0
Complete Mix	1,000	261,800	6,100	34,300	21.4
Plug Flow	1,000	190,300	4,400	24,900	16.1
Hog Farms					
Covered Lagoon	500	48,900	1,100	6,000	5.7
Complete Mix	500	86,000	1,000	6,400	9.1
Covered Lagoon	1,000	71,700	2,300	12,000	7.0
Complete Mix	1,000	112,000	2,000	12,700	10.6

Table 10. Costs and benefits of livestock methane recovery and electricity generation systems. Recovery system costs for covered lagoons do not include the cost of the lagoon itself. For dairy farms, average gas recovery rates and electricity rates for Erath County, Texas are applied. For hog farms, average gas recovery rates and electricity rates for Sampson County, North Carolina are applied. Plug flow systems do not include slurry from pens. Average weight of cows is 1,400 lbs., and that of hogs is 138 lbs. From EPA, 1993b, p. 6-38-6-40.

This table suggests that, under the right conditions, a wide range of farm sizes may be able to profitably generate electricity, at least on the mainland. Undoubtedly, conditions are different in Hawai'i, in particular the lack of any hog farms over 350 head in size. But ventures collecting manure from several nearby farms in Hawai'i do appear to merit further study.

The primary drawback to methane collection from lagoons in Hawai'i is the lack of cost effectiveness when confined to a single farm. An important aspect of the cost is the corrosivity of some of the gases produced, in particular hydrogen sulfide (H_2S). Mitigation measures which reduce this gas also have costs involved: For example, use of absorbents such as iron oxide adds labor and transportation costs for disposal (Hoeksma, 1986, p. 93). Once the methane has been collected, it may be either flared, burned for heat, or burned or sold for electricity. Flaring produces no net benefit aside from a reduced global warming potential. Burning for heat may be beneficial, especially for farms at higher elevations where piglets need heated pens (Zaleski, personal communication); but since most farms do not require the amount of heat that can be generated, much of the heat is inevitably wasted (EPA, 1993b, p. 6-23).

However, of the various options available to livestock managers in the state for reduction of methane emissions from their animals, covered lagoons tend to offer the least retooling of current waste management systems and the least long-term cost (EPA, 1993b, p. 6-22 and 6-23). Dairy and swine operations in particular keep the animals in enclosed pens from which the manure is collected by flushing with large quantities of water. The substantial dilution which results generally prevents solid waste management techniques such as composting from being either operationally or economically feasible (EPA, 1993b, p. 6-23; Zaleski, personal communication).

Hawai'i has some experience with this approach. From 1991 to 1995, the Happy Hula Hog Farm in Kula, Maui used hog manure to generate 20 kW of electricity. A 61,000 gallon biomass digester with a floating cover was used to produce biogas, from the waste slurry of about 150 to 160 sows, which fueled a generator system. Due to the small amount of biogas produced, the system could only operate 8 to 10 hours per day and was primarily used as a backup to utility power. Component failure caused its shutdown in 1995, and plans by the owners to sell the farm have prevented its repair (Greer, 1997, p. 16). A manure digester used on a hog farm on Kaua'i has also produced biogas used to run a generator, but the low concentration of methane in the biogas (~60%) has made it necessary to use a fuel mixture of 3/4 diesel and only 1/4 biogas (Zaleski, personal communication).

A biogas plant operated by Unisyn, Inc. in Waimanalo also gets most of its material from a 1,200-head dairy farm nearby. Since the plant augments this manure with material from several other sources, it is discussed more fully in the next section.

c. *Provide incentives for transfer of waste slurries to centralized waste-to-energy plants.*

While waste-to-energy plants at individual farms are generally not cost-effective unless the farms are of moderate to large size, combining the waste from a group of neighboring farms is often significantly more economical. For example, this could involve construction of one or more small, Unisyn-type plants on each island. Unisyn (Universal Synergistics) Biowaste Technology is a Seattle-based company which has been running a unique bioconversion plant in Waimanalo, at the east end of O'ahu, since 1986. This plant processes about 35 tons per day (13,000 tons per year) of wet organic waste--including animal manure from a 1,200-head dairy, food waste, and (since 1995) green waste. Capacity is 110 tons per day of wet organic waste and 30 tons per day of green waste. The process is centered around anaerobic digestion, wherein the waste is converted into biogas, granular fertilizer, compost and irrigation water. The biogas fuels a generator which satisfies most of the facility's energy requirements. The fertilizer and compost are sold to plant nurseries, golf courses and landscapers, and the irrigation water is kept for moisture needs or donated to local farmers via a plastic pipeline. This water has been approved by the DOH for use on soybeans, corn, bananas and other crops (Lyum, personal communication; EPA, 1993b, p. 6-26).

As seen in Table 9 above, it may be possible to run a handful of slurry-to-energy plants in Hawai'i. To take swine as an example, there may be an opportunity to build two centralized waste-to-energy plants along the west coast of O'ahu using animal slurries from surrounding farms. Although the average size of the 350 or so hog farms in Hawai'i is only on the order of 50 to 100 hogs, it is estimated that approximately 50% of the hogs in the state are raised in this area due to zoning restrictions. While such restrictions may be barriers elsewhere (see below), here they may prove a boon by providing the proximity necessary to allow pipeline construction costs and hauling fees to become economical. As such, it may be possible to construct one plant serving the Wai'anae area and another serving Nanakuli farms. Ownership could be either by a separate entity or through joint ownership with neighboring farms. A precedent already exists in the form of the Producer's Co-op, which runs the area's slaughterhouse.

However, even a plant using slurry biogas from several farms may be insufficient without upgrading of the gas, which is typically only about 60% methane. The best use of such gas is probably for heating rather than electricity generation (Zaleski, personal communication). The key is finding a customer in need of heat, such as the quarry which receives heat from the methane emanating from Kapa'a Landfill to dry its aggregate (*Honolulu Advertiser*, May 26, 1997, p. A22).

Setting up a centralized, Unisyn-type plant for livestock biomethanation would have both positive and negative aspects.

Benefits would include (Hoeksma, 1986, p. 94):

- Cost reduction per cubic meter of digester volume.
- Smoother input, since variations in feed from one farm are partially mitigated by feed from other farms.
- The opportunity to site the plant for maximum use of available animal waste.

Disadvantages would include:

- Added costs for transport to the plant (possibly counterbalanced by increased proximity to fertilizer and/or energy market).
- Increased complexity of administration.
- Possible worsening of odors around the plant.

Government initiatives for increasing the capture rate for methane emissions from animal manure could include both incentives and regulations. Possible incentives include tax rebates, low-interest loans and training workshops. Regulations could mirror those of several other states which currently require farms to more stringently manage their animal wastes (EPA, 1993a, p. 6-24). Care must be taken, however, to ensure that such anaerobic digesters are working properly; when not working optimally, these can actually increase methane emissions from animal waste (EPA, 1993a, p. 6-25).

One broad-brush method for government involvement is through the U.S. AgSTAR Program, a voluntary pollution prevention program operated in conjunction with the livestock industry. The program encourages dairy and hog farms to adopt "best management practices" which profitably manage animal manure, while reducing pollution and fertilizer costs. This program seeks to overcome a number of barriers that currently hinder the more widespread use of on-farm energy recovery technologies, including lack of information and technological support. This program is also part of the U.S. Climate Action Plan (Hedger, 1996, p. 24 and 26).

A more intensive and localized program could follow the example of Missouri, which recently began a cooperative venture with local livestock and poultry producers, in conjunction with the EPA. In this program, the relevant state agencies work together through the State Revolving Loan Fund, the sale of water pollution control bonds and federal capitalization grants to finance animal waste treatment systems at below conventional interest rates (EPA, 1996b, p. 5). Creative measures like this will likely be necessary to put animal waste management systems into use in Hawai'i.

2. Improve the Diet Quality of Ruminants (low to moderate cost, moderate benefit)

Much of the food eaten by cattle, sheep and goats (but not hogs) cannot be digested until it has been fermented. This process takes place in the part of the digestive system called the rumen, by bacteria that produce methane as a by-product of the fermentation process. The efficiency of methane formation in the rumen varies with animal type, the type of fiber in feed, the level of feed intake and the retention time of fiber in the rumen. Animals fed forage (grasses and legumes) tend to produce more methane per unit of feed dry matter than animals fed diets rich in readily-digested concentrates (especially grains) (Kirchgessner et al., 1995, p. 333-348). This is the opposite of the effect of readily-digested feed on manure, as might be expected since the organic matter not utilized by the rumen must pass on through (EPA, 1995c, p. 61). Yet the digestibility of feed should nevertheless be increased where possible, in spite of this contradiction, for two reasons: First, overall emissions in Hawai'i from manure are less than those from rumination (see Figure 1a). Second, reduced emissions from rumination also tend to be associated with improved animal productivity (IPCC, 1991, p. 111).

In Hawai'i, the two main classes of cattle are dairy cattle and beef replacement cattle (0-12 months old). The former generally graze on pasture, while the latter tend to be raised in feedlots. Of the beef cattle kept in feedlots on Maui, 10% to 15% finish on grass (Moniz, personal communication).

a. *Promote and support research into economically viable diets for dairy cattle and pasture supplements for beef cattle which increase productivity without increasing methane emission rates, emphasizing maximization of nitrogen-fixing crops where possible.*

   Typical feedlot diets in the U.S. consist of only about 15% forage and about 85% "concentrate ration," which consists mainly of grains (EPA, 1993b, p. 5-33). In the Maui feedlots, the main feed is pineapple silage, supplemented by protein sources such as soybeans or cottonseeds from time to time (Moniz, personal communication). Dairy farmers tend to balance reasonable price with cattle needs, buying feed in bulk from the mainland and mixing it onsite, again adding a protein source. Dairy cattle diets tend to have a higher percentage of forage, considered necessary for proper milk production. However, the EPA has concluded that opportunity still exists for dairy farmers "to increase grain feeding in response to changes in milk pricing" (EPA, 1993b, p. 5-30). Such changes would of course be market-driven, but opportunities would remain for the state to help educate consumers and farmers regarding the benefits of altered diet.

   For grazing animals, supplementing forage with minerals and protein sources is an important way of increasing the efficiency of pasture use. Supplements such as whole cottonseed appear to be particularly promising in terms of reduced methane emissions (IPCC, 1991, p. 112). The potential for improving the nutritional status of grazing animals using supplements is considered to be greater in tropical regions than in temperate regions because tropical forages have a higher fiber content and are thus of lower digestibility than temperate forages (Joblin, 1996, p. 441). It is uncertain where Hawai'i's grasses fall on the digestibility continuum, but the subject merits further study.

For developed countries, some researchers have estimated that methane emission reductions on the order of 25% are possible in some cases by using both nutritional supplements and growth hormones such as bovine somatotropin (bST) (Joblin, 1996, p. 442-443). However, public concern is growing regarding the impacts of the latter on human health (IPCC, 1991, p. 111), and the EPA predicts that bST alone would only be responsible for 3% to 7% of all foreseeable reductions in methane emissions from cattle in the U.S. (EPA, 1993b, p. 5-4). It has also been recommended that feed be supplemented with ionophore antibiotics which kill methane-generating bacteria in the rumen. However, these techniques are generally only feasible for confined cattle (cattle kept in pens or feedlots), and methanogenic bacteria can become resistant to antibiotics (OTA, 1991, p. 253-255; Joblin, 1996, p. 442-443).

Some studies have further concluded that supplementing cattle feed with urea—a common practice on the mainland—causes a noticeable drop in methane emissions. Very little urea is fed to cattle in Hawai'i, however, both because it is used mainly for fattening and because maintaining a proper proportion is a risky operation which, if done improperly, can kill the cattle (Rauson, personal communication).

The EPA has concluded that improved forage and nutrient supplements alone can decrease methane emissions from dairy and beef cows by 30% to 45%, while increasing productivity by an equal amount (Tables 11 and 12). The main methods recommended for forage improvement are improved fertilization schedules and a thorough understanding of nutrient needs (EPA 1993b, p. 5-4 and 5-24 to 5-25). Comparisons of various diets for both metabolizable energy (ME) and methane production in EPA tests are shown in Tables 11 and 12.

Lactation Diet (Fed 305 days/yr; replaced by Diet #9 the other 60 days)	Diet ME (Mcal/kg)	Methane/ME (kg/ME)	
		Study A	Study B
1. High quality alfalfa hay (20% protein)	2.4	59.1	58.7
2. 75% alfalfa, 25% corn-soybean meal	2.5	53.6	41.9
3. 60% alfalfa, 40% corn-soybean meal	2.5	49.0	46.6
4. 50% alfalfa, 50% corn-soybean meal	*2.6*	*44.4*	*40.2*
5. 60% alfalfa, 40% corn-cottonsead meal	2.6	50.8	50.0
6. 50% alfalfa, 50% barley-soybean meal	2.6	45.5	41.2
7. 40% alfalfa, 54.5% cornmeal, 5.5% soybean meal	*2.7*	*34.1*	*37.0*
8. 40% alfalfa, 54.5% oatmeal, 5.5% soybean meal	2.6	41.8	46.0
9. Timothy hay (9% protein), plus some cottonseed meal	2.4	56.4	57.3
10. 40% timothy hay, 45% cornmeal, 15% soybean meal	2.7	45.7	47.6
11. 70% corn silage, 16% cornmeal, 14% soybean meal	2.7	42.6	45.3

Table 11. Methane emissions per unit of metabolizable energy (1 ME = 1 Mcal/kg of feed) for a variety of dairy cattle diets. After US EPA (1993), p. 5-10.

	Diet 1 Legume Pasture with Supplement	**Diet 2** Very High Quality Grass (18% Protein)	**Diet 3** Corn Silage with Supplement
Diet ME (Mcal/kg)	2.48	2.58	2.66
Methane/head (kg/head)	18.1	27.2	15.8
Methane/head/ME	7.3	10.5	5.9
Percent of Farms Using	50%	50%	0%

Table 12. Simulated methane emissions per head of beef replacement cattle (0-1: months in age) on three separate diets, compared to each diet's metabolizable energy (1 ME = 1 Mcal/kg of feed). After US EPA, 1993b, p. 5-21.

Table 11 shows that, for dairy cattle, mixtures of approximately half alfalfa hay and half corn-soybean meal cause both high productivity and low methane emission rates. The highest emission rates for dairy cattle are produced by diets which consist essentially of hay (alfalfa or timothy) alone. Unfortunately for our recommendation made elsewhere in this report regarding planting of nitrogen-fixing crops, the best dairy cattle diets are also those lowest in such nitrogen-fixing crops as hay and soybeans.

Similarly, beef cattle productivity is highest--and emissions lowest--on a diet consisting mainly of corn silage. As can be seen in Table 12, this diet is rare to absent across the western U.S., although half of all farms graze on clover and other legumes. In Hawai'i, most pastures are grass rather than clover. Although legume forage is less efficient in terms of its conversion into energy (and meat), any change toward a more legume-rich (or grain-rich) diet would have positive results in terms of methane emissions. Thus, the feasibility of increasing legume and grain supplements to beef cattle diets—or seeding pasture with legume ground cover—should be carefully studied. It must be kept in mind, however, that for all livestock operations in Hawai'i, any efforts to reduce greenhouse gas emissions must also be cost-effective when implemented or the industry will likely oppose these measures (Moniz, personal communication).

It should be noted that the values in Tables 11 and 12 have been produced via model simulations, then verified through observations of animal performance. Although the resulting uncertainty is $\pm$ 20%, the general conclusions of these tables appear to be valid, and have been accepted as representative by the EPA (EPA, 1993a, p. 5-34).

Side benefits of improving the diet quality of ruminants:

- Lowering methane production in the rumen will increase the amount of energy captured from forage by the animal, thus improving animal productivity.
- Healthier, more profitable products will be produced.

Drawbacks:

- Increased use of grain decreases market for nitrogen-fixing plants and increases the percentage of crops not intended for direct human consumption.

To achieve decreased methane emissions from ruminants will require considerable research and development. The ideal scenario is to increase the individual performance and productivity of ruminants. Intensive management is the most important factor because of the variability involved. The feed efficiency of ruminants can vary according to animal type, health (especially degree of parasitism; see below) and age. For example, yearling cattle require a diet higher in protein than do adult cattle (Zaleski, personal communication). Specific feed mixtures are difficult to recommend for Hawai'i, because all the feed is manufactured on the mainland. Different mixtures that work well elsewhere may not achieve the same production levels in Hawai'i. Therefore, trial-and-error processes and comparisons of different management techniques remain the major means of improving overall ruminant performance in Hawai'i.

Although such efforts will largely be market-driven, ostensibly leaving the state and county governments with little to do, one key to the success of such efforts is careful recordkeeping regarding feed type and tonnage purchased, and resulting growth rate and market value, both within and between growth cohorts or litters. The state and counties can help by designing, promoting and perhaps mandating specific forms in order to normalize such recordkeeping (Zaleski, personal communication). In particular, these bodies can participate in the U.S. Ruminant Livestock Methane Program, a partnership between the EPA, the USDA and livestock producers which aims to increase livestock productivity while reducing costs, producing healthier products and reducing methane emissions. The program, which has been incorporated into the U.S. Climate Action Plan, seeks to implement all of the measures discussed above (Hedger, 1996, p. 23).

There is at least one more option for which the government could provide aid, an option which is also addressed by the U.S. Livestock Methane Program. It is known that reducing the fat content of milk and beef also results in reduced methane emissions from these animals, reinforcing an ongoing decrease in fat intake by Americans. Indeed, the EPA predicts that this trend could be responsible for 45% to 65% of all foreseeable reductions in methane emissions from dairy and beef cattle (Table 13). Such reductions occur in part due to changes in feed, but also due to changes in breeding and management of beef calves (EPA, 1993a, p. 5-42; EPA, 1993b, p. 5-4, 5-32 and 5-33). Again, this change is largely market driven. In Hawai'i, cattle ranchers adjust by artificially inseminating their stock to improve its genetic makeup, in an effort to produce lean carcasses for which processors pay top dollar (Zaleski, personal communication).

Option	Description	% of Total Reductions
Dairy Farms (33% of Total)		
Improve Dairy Cow Productivity	Continue to improve nutrition management and genetics	10-15%
	Use bST to improve production	3-7%
Refine Milk Pricing System	Adjust rations to reduce milkfat and methane emissions	10-20%
Beef Farms (67% of Total)		
Improve Beef Production Productivity	Continue to use nutritional management to improve cow-calf reproductive performance	20-30%
	Improve feed efficiency via ionophores	5-15%
Refine Beef Marketing System	Provide information to help market incentives reduce trimmable fat	4-6%
	Provide information to help market incentives move calves directly to feedlots, further reducing fat	20-30%

Table 13. Summary of cattle methane emissions reduction options in the US. Does not include total magnitude of all options combined. From EPA, 1993b, p. 5-4.

b. *Educate markets and consumers regarding the combined health benefits and reduced methane produced by low-fat cattle products.*

Efforts by the state to further educate markets and consumers in Hawai'i regarding the combined health and reduced methane benefits of low-fat cattle products would help to improve both health and the state economy while reducing greenhouse gas emissions. In particular, the state could support and augment the "Value-Based Marketing" initiative begun by the beef industry in the early 1990s (EPA, 1993b, p. 5-32). In 1993, the EPA calculated that eliminating the creation in the first place of all fat subsequently trimmed from beef would save about $2 billion per year nationwide. Assuming that 4% of gross energy intake in a steer is normally converted to fat, this savings translates to a nationwide reduction in methane emissions of about 120,000 tons per year (EPA, 1993b, p. 5-32 and 5-33). Unfortunately, the costs of such a program have apparently not been quantified.

3. Improve Efficiency of Livestock Feed Application (low cost, low to moderate benefit)

a. *Improve monitoring and design of feed bins.*

Often up to 25% of feed is directly wasted, especially on cattle and hog farms. Better monitoring of the feeding process and improved feeding bin designs would reduce this wastage, as well as emissions from decomposing feed.

b. *Maintain a good parasite control program.*

Parasites reduce the efficiency of feed uptake and reduce the health of the animals by sapping fluids and nutrients from livestock.

4. Increase Aerobic Treatment of Manure (low cost, moderate benefit)

a. *Expand the market for composted manure as fertilizer.*

Composting is the aerobic decomposition of organic material to produce a soil amendment. Onsite composting occurs on many livestock farms in Hawai'i. For example, nearly all of the dairy cattle manure on O'ahu is being composted onsite and then applied to pineapple fields (Lee, personal communication). Swine owners have attempted to market their compost fertilizer as well, but often lack the necessary funds and management capabilities (Zaleski, personal communication). Instead, most of Hawai'i's swine waste systems are composed, at least in part, of open lagoons which are anaerobic below the top few inches of slurry. Such lagoons predominate because they provide the cheapest long-term method for dealing with animal excrement, with costs generally in the range of $100 to $200 per lagoon, with lifetimes averaging 15 years (Zaleski, personal communication). On the other hand, lagoon systems dilute manure considerably, making it costly to transport the treated effluent offsite (EPA, 1993b, p. 6-14).

Yet composting can be a cost-effective method for managing livestock manure. On O'ahu, composted dairy cattle manure currently sells for \$30 per yd^3, compared to approximately \$10 per yd^3 for unprocessed dairy solids (Zaleski, personal communication; Hawaiian Earth Products, Ltd., 1995). If the composting process costs less than this difference, then composting would be the preferred disposal method. Currently on O'ahu, only one hog farm has an aerobic composting system which operates completely outside the animal pens, yet this operation appears to be turning a profit (Zaleski, personal communication). The neighbor islands appear to be particularly suited to compost marketing, with dairy cattle compost occasionally commanding in excess of $300 per yd^3 (Zaleski, personal communication).

i. Provide expertise and financial incentives to swine and poultry owners who wish to compost and market their manure, targeting systems which mix the manure with green waste. Most of the composting operations described above, as well as essentially all of the methane-generating operations described below, were made possible by county, state or federal grants. It appears that most farms must not only be of a certain size to be economical to operate commercially (at least 20 animals for cattle and hog farms), but must be of a significantly larger size to maintain a cost-effective composting operation (at least 100 animals for cattle and hog farms). Thus, any grants or loans should be restricted to those operations currently at or near the point of cost-effectiveness (Zaleski, personal communication). This minimum size can be reduced somewhat if these livestock operations also maintain crops on their farms. For example, one hog farm in Na'alehu on the Big Island uses its compost to fertilize its stands of coffee trees and ti plants (Zaleski, personal communication).

   In situations where several farms are clustered together, as in the Wai'anae district of O'ahu, a central composting system is possible. Again, funding would need to come from government sources, but the possibility exists that land will be offered for free from private landowners. Indeed, land was offered recently for just such an operation by the Lualualei Golf Course, which hoped to use the compost on its grass. Unfortunately, the area available was determined to be insufficient for the needs of the facility, and the project was shelved (Zaleski, personal communication).

ii. Identify and work to eliminate any significant obstacles to the integration of livestock and crop production operations. Currently, there are two policies hindering wide-scale composting on O'ahu, and similar hindrances may exist in other counties. The first is a land-use policy. On O'ahu, agricultural lands are divided into Agricultural Zone 1 (AG-1) and Agricultural Zone 2 (AG-2). While the county allows livestock raising, composting and crop production in both zones, large-scale livestock operations are restricted to AG-1 land (City and County of Honolulu Chapter 21, Article 5.20). This distinction has increased the average distance between potential compost suppliers and potential compost users, causing transport to rise to roughly $200 per 4000-gallon load (Zaleski, personal communication). On the other hand, it is this very clustering of larger livestock operations which may make large-scale composting possible in the first place. Since it is unlikely that the county will rescind its zoning laws, an important consideration in any grants or loans should be meeting the costs of transportation.

iii. <u>Reduce the permitting process for farms which desire to transport composted material to offsite customers.</u> The second, and more important, policy hindering wide-scale composting on O'ahu is the fact that on-site composting on both AG-1 and AG-2 land is a conditional use; i.e., it is allowed only with a permit from the county. This requirement applies even to minor composting operations on AG-1 land (City and County of Honolulu Chapter 21, Article 5.20). Since AG-1 land is designed to be removed some distance from residential areas anyway, it appears possible that permits could be waived for both small-scale and large-scale composting operations on this land if certain guidelines are followed. Unfortunately, largely as a result of negative feelings about the Unisyn plant, two bills introduced in the last session of the state legislature (HB 2244 and SB 1666) failed to pass. These bills would have specified that composting be a permitted use in the agricultural district.

Composting on any land appears to be problematic at present in Hawai'i. All composting operations must apply first for conditional use permits, then another round of permits for the actual composting process. Both sets of permits can require extensive time for approval. For example, it took the Hawaiian Earth Products company approximately three years to obtain an air quality permit to compost green waste and dairy manure at Campbell Industrial Park (Zaleski, personal communication). Removing these hindrances will require extensive consultation and public education, but it is in the best interest of everyone in Hawai'i for the state and county governments to continue working to resolve this problem.

Side benefits of composting:

- Increases water retention potential of soil more than most fertilizers, hus reducing water requirements.
- Provides an alternative to chemical fertilizers that cause more chemical contamination of water resources and require more energy to create.
- Reduces odor problems, as composting operations typically emit less odor than manure lagoons.
- When co-composted with biosolids, the high nitrogen and phosphorus levels in the biosolids complement the high carbon levels in the green waste.

b. *Direct land application for aerobic decomposition.*

Direct land application involves mechanically dumping and spreading livestock manure or slurry as a fertilizer on pasture or forage crops. The solid component of manure is deposited on the soil surface, while the liquid component can be injected under the soil surface.

i. Evaluate costs and benefits of injecting animal slurry into soil as a crop amendment. To date, soil injection has only been attempted on Lana'i, at a hog farm which has since gone out of business (Zaleski, personal communication). It has been demonstrated that injection of waste slurry 4-6 inches below the surface with mechanical injectors can increase yields of corn more than 200% over surface spreading in certain soils, with lower emissions of nitrogen to the atmosphere (Larsen, 1986, p. 77). However, this method is not only slower than surface spreading, it is also much more expensive. Indeed, the method which appears to best combine effectiveness and low cost is surface spreading, followed by simply turning the slurry into the soil with a shovel or plow depending on the size of the farm (Zaleski, personal communication).

   More research needs to be done regarding the relative effectiveness of surface application and subsurface injection of liquid slurries. In Europe, some researchers have concluded that the yield increases noted above for surface application may be applicable only to crops; broadcast spreading on pastures has actually been found to decrease the quality and palatability of grass to livestock (Kemppainen, 1986, p. 64). On the other hand, one hog farmer in Kamuela on the Big Island has set up an irrigation system to apply his lagoon-stored slurry to pasture, concluding that grass growth has increased 500% with no loss of palatability. Since this farmer is currently in the process of shipping over a larger-caliber hose system to improve application rates on his mid-size farm and reduce clogging, there appears to be potential for this method which merits further study (Zaleski, personal communication).

ii. Promote storage of manure in closed tanks or pits. Much of Recommendation 'a' applies to direct land application of livestock manure, especially the importance of transport costs in determining whether or not this measure would be cost-effective in reducing methane emissions. Under aerobic conditions, livestock manure produces very little methane. This is the reason that beef cattle manure is not a significant source of methane, since beef cattle excrement is deposited primarily on open farmland or pasture.

As for nitrogen emissions, studies in Europe have found that waste slurries which have simply been stored in closed tanks or pits volatilize the least amount of nitrogen after they have been applied to fields (Tables 14 and 15).

Animal Type	After 7 Days Storage in Closed Pits	After Aerobic Treatment	After Anaerobic Digestion
Cattle	1.86%	1.83%	1.88%
Pig	5.14%	5.12%	5.05%

Table 14. Total nitrogen contents of various animal waste slurries. From Suess and Wurzinger, 1986, p. 48.

Animal Type	After 7 Days Storage in Closed Pits	After Aerobic Treatment	After Anaerobic Digestion
Cattle	12.8%	11.6%	28.4%
Pig	11.4%	26.5%	25.6%

Table 15. Nitrogen losses from various animal waste slurries after 7 days exposure to air. From Besson et al., 1986, 43.

Nitrogen is emitted in greatest amounts from anaerobically-treated slurry, mainly due to a significant portion of its organic nitrogen being converted into ammonia (NH_4). While ammonia is not considered a greenhouse gas, it can react with oxygen to form N_2O and NO_x (Besson et al., 1986, p. 43; Suess and Wurzinger, 1986, p. 53).

Side benefits of direct land application have been found to:

- Improve overall soil structure as the organic material increases nutrient- and water-holding capacity.
- Reduce runoff and soil erosion (due to improved soil structure) thus making the soil easier to plow.
- Increase the pH of acid soils (Reinhart et al., 1996, p. 4).

Swine and poultry manures typically contain more nitrogen than dairy manure (Zaleski, personal communication). Because of this, dairy manure can be composted with soil in direct land application, while swine and poultry manures compost quicker and better mixed with green waste, although direct land application is still an option. This is because effective composting requires a proper carbon/nitrogen ratio.

A comparison can be made between Recommendations a and b. The benefits of composting include an essentially odor-free product that can bring a monetary return. On the other hand, the composting process also requires substantial additional labor and management, as described in No. 1. of the Fertilizer section below. In addition, direct land application retains all the fertilizing value of livestock manure whereas the composting process consumes a portion of the nutrients which could otherwise be utilized (Zaleski, personal communication).

In Hawai'i, the main drivers for manure management are DOH regulations and technical advice from DLNR. Educational workshops are provided by the U.S. Department of Agriculture (USDA), but essentially no other incentives for comprehensive manure management operations are offered by either the county, state or federal governments (Moniz, personal communication). Clearly, there is room for improvement in this regard.

As the lack of a magnitude for the total emissions reduction in Table 13 exemplifies, few applicable studies have calculated the net emissions reduction to be expected from various measures to reduce greenhouse gas emissions from livestock rumination and manure management. However, some assurance in calculations is provided by the state's prediction that agricultural wage and salary jobs are expected rise only moderately from the current 7,500 to peak and then remain level at 8,000 jobs after 2000, following some adjustment as a portion of farmers move into diversified agriculture (State of Hawai'i, 1997a, p. 20).

C. Fertilizer and Compost

The primary concern regarding fertilizer application is the volatilization of nitrous oxide (N_2O). Globally, agricultural processes contribute approximately 70% of anthropogenic N_2O emissions, predominantly via fertilizer application (Energy Information Agency, 1995, p. 46). Although some studies claim that there is no correlation between fertilizer type and emissions rate, most researchers agree that emissions are actually a function of a variety of factors, including fertilizer type (especially slow-release vs. fast-release), soil moisture, soil type and whether irrigation or rainfall occurred shortly after application (Energy Information Agency, 1995, p. 46-47). Fertilization increases N_2O emissions from soil between 1.7 and 6.6 times what the soil was previously emitting (Energy Information Administration, 1995, p. 73). The following recommendations attempt to take these considerations into account.

1. Promote expanded use of organic fertilizers (low to moderate cost, moderate to high benefit)

a. Initiate and support diversion of more green waste to municipal, county and private composting and mulching factories.

i. Concentrate on aerobic and dry anaerobic methods. As noted in the Landfills section above, although one might think that diverting green waste and food waste to composting operations would reduce the volume of methane that landfills can generate for power, this is generally not the case. Instead, overall proportions of waste types are more or less retained due to other materials being removed from the waste stream at approximately the same rates as green waste. In addition, Hawai'i generates a greater volume of green waste per capita than do mainland states due to its subtropical climate; thus, it can be argued that diversion of a moderate amount of green waste would have little effect on landfills. Furthermore, composting would only affect methane generation during the first few years after the green waste's diversion. Since all but the largest landfills in the state are at the lower end of the size spectrum for economic methane production, a substantial diversion of green waste could move a marginally profitable landfill into the red, but overall the benefits of green waste composting appear to outweigh the possible negative impacts on landfills (State of Hawai'i, 1984, p. 52).

Green waste composting utilizes bacteria which are naturally abundant in organic matter and which facilitate the decay of cellulose and other plant matter. Oxygen, temperature, moisture, acidity, and nutrient levels must be properly managed to create a maximum amount of useable compost. A notable benefit from the standpoint of greenhouse gas emissions is that grass clippings, when incinerated, can be a significant source of nitrogen oxides (NO_X)--a source which is eliminated when such clippings are composted (EPA, 1989, p. 91).

In 1988, the Noyes Data Corporation published a rigorous benefit/cost analysis of composting methods on the mainland. The three methods studied in the analysis were the aerated static pile, conventional windrow (Figure 15) and aerated windrow methods. Unfortunately, this analysis was unable to produce a definitive comparison of composting methods in terms of overall costs and benefits. Yet the study was able to conclude that all three methods were capable of sustained production of 0.4 to 1.0 yd^3 of compost per wet ton of sewage sludge, weighing 900 to 1,500 lb/yd^3. The aerated static pile method--the only method for which costs were available--cost $36 to $51 per wet ton of sludge, not including transport or dewatering. The static pile method required a minimum of 21 days per composting load, while windrow methods required a minimum of 30 days. No data were collected on gas emissions or profit from compost sales (Benedict et al., 1988, p. 12-15).

The EPA (EPA, 1989, p. 83-85) has also determined general, relative costs for various aerobic composting methods. As a result, the EPA ranks them as follows: (1) large windrow, (2) conventional windrow, and (3) aerated windrow methods. Large windrows tend to be cheaper (due to more infrequent turning), but require more time (1-3 years) and area (due to greater odor problems and the resulting need for a wider buffer zone) than other methods. Aeration reduces time (to about a year) and area (due to reduced odor), but is significantly more expensive due to added

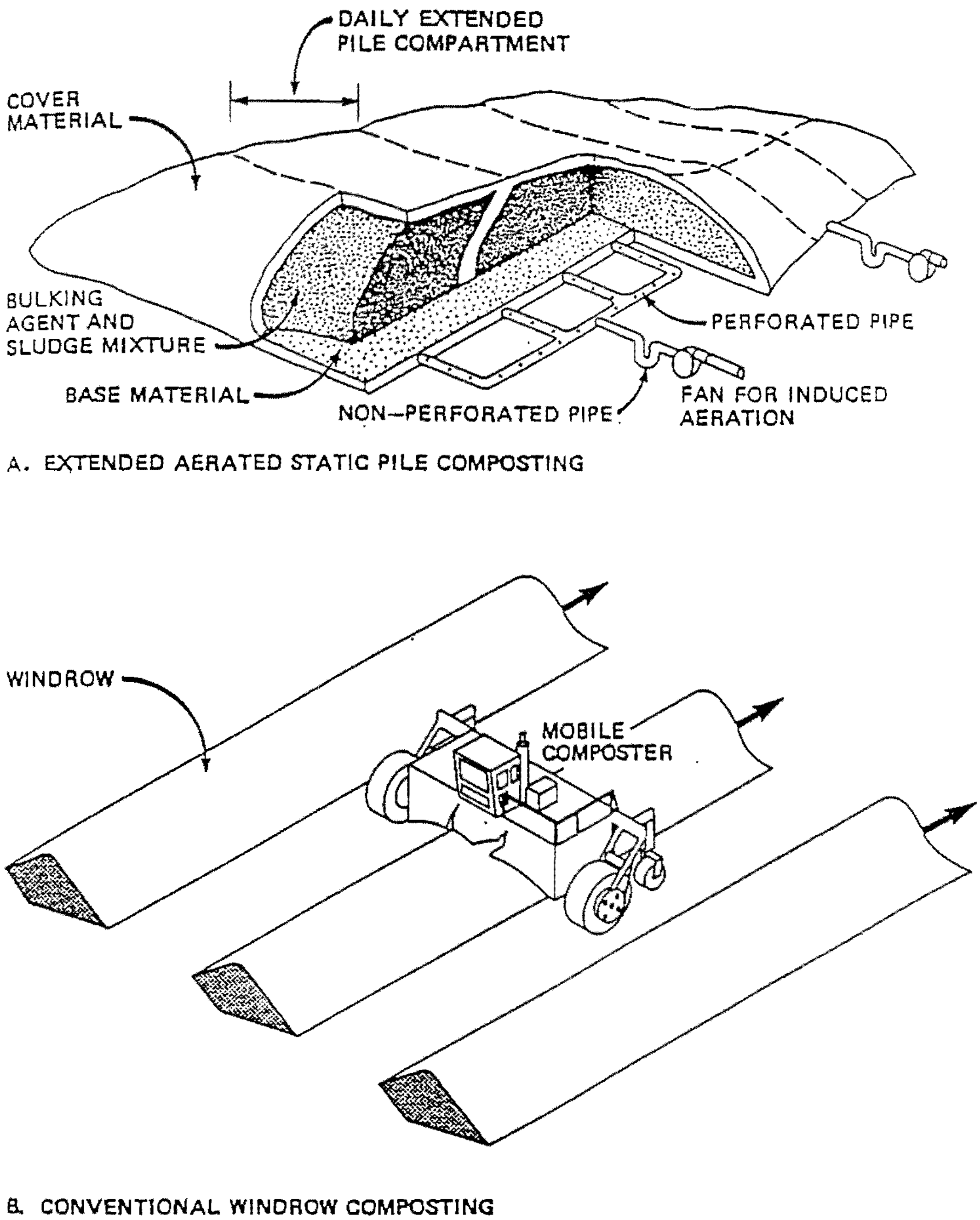


Figure 15. Common sludge composting methods. From Benedict et al., 1988, p. 5.

infrastructure and labor needs. An additional problem is that composting facilities tend to violate the economies of scale.

Taking facilities using large windrows in the late 1980s as an example, medium-sized facilities (20,000 to 30,000 cubic yards) cost an average of $4 per cubic yard to operate, while larger facilities (80,000 cubic yards or more) tended to cost about $6 per cubic yard (EPA, 1989, p. 86).

Dry anaerobic composting is another method which has proven cost-effective, since the resulting methane can be captured and utilized for energy production in the composting facilities. Dry anaerobic composting also reuses the water necessary for compost production, thus allowing reuse of the composting bacteria which it contains. Dry anaerobic composting is particularly applicable to the conditions in Hawai'i since it does not require as much land or water as does wet composting.

Each representative from the four county solid waste programs has stated that the amount of composting has increased over the last decade and will continue to expand in the coming years. For example, on O'ahu the 25,000 tons of green waste and 12,000 tons of food waste composted in 1996 will continue to grow in the coming years, although at a decreasing rate. One program which shows particular promise on O'ahu is a series of workshops explaining the techniques and benefits of backyard composting. The amount of food waste in particular is likely to remain stable over at least the next couple of years due to a lack of price incentives. The City and County of Honolulu is also considering the composting of sewage sludge in the future (Harder, personal communication; McCabe, personal communication).

In 1996 Maui composted approximately 14,000 tons of green waste and 19,000 tons of wet waste (sewage sludge and food waste). This tonnage has grown rapidly since 1993, but projections are for this growth to begin to level out in the near future (Figure 10).

For Kaua'i and the Big Island, the tonnages composted are estimates only. For 1996, the best estimates are 4,000 tons on Kaua'i and 1,200 tons on the Big Island. Since Kaua'i does most of its composting through private corporations, it is difficult to know the exact tonnages being composted, both in total and according to waste type. It appears that few companies are attempting to compost on the Big Island, with small groups of people taking it upon themselves to compost instead. Some compostable products of commercial activities, such as macadamia nut husks, are burned instead to power onsite equipment. The Big Island first initiated, then suspended, a composting contract with private operations (Harder, personal communication; McCabe, personal communication).

The state government has a role to play as well. For example, it can make a larger commitment to utilize local compost for landscaping, since most of the compost used in state-funded landscaping still comes from the mainland. This will require changing regulated specifications in compost material, but the state has moved partway to this goal through its recent guarantee to developers, architects and landscapers that local compost will be of comparable quality to mainland compost (McCabe, personal communication). Assuredly, more research needs to be done on the benefits and economics of aerobic composting for the Hawai'i area.

In particular, studies should investigate developing aerobic composting so as to produce a natural slow-release fertilizer for commercial or personal use. The state has also found that composting for use onsite is most successful when farmers are reusing effluent as well (Yee, personal communication).

ii. Advertise and educate the public regarding existing programs, especially for home pickup of separated green waste. While curbside pickup and centralized dropoff points for green waste are currently in place in parts of Honolulu and elsewhere (McCabe, personal communication), these programs remain poorly advertised and most people capable of taking advantage of them remain unaware of these programs' existence. The public needs to become aware of the benefits of composting, even though many of these benefits may be more for the long term. Encouraging the public to separate their green waste with some sort of incentive program is always helpful in getting the cooperation needed for further success. The idea of private composting should also be encouraged, for example in home gardens and greenhouses. With private composting, usage of nitrogen-rich fertilizer is reduced, saving money as well as greenhouse emissions.

Educating the public on the potential of composting facilities is very important for future success. This factor is especially important as community boards have assumed an increasing influence concerning the development of industrial facilities. There have been examples of community boards blocking the construction of waste management and composting operations. In one recent case, an attempt by the state to create a large-scale dairy operation with a sophisticated wastewater facility was canceled due to opposition by the community and their legislators (Yamamoto, personal communication). Numerous complaints have also been voiced regarding the Unisyn operation in Waimanalo (*Honolulu Star-Bulletin*, January 14, 1997, p. A3) (see section on Crop Burning below). The public must begin to realize that a well-managed composting facility can have many benefits (as described in previous sections) and should not be considered a blemish to the local community. As noted in the Action Plan below, county governments can provide financial incentives to companies and individuals to increase composting rates, as well as provide relevant information.

iii. Promote mulching. Mulch consists of an organic and/or inorganic material which is spread over soil to reduce erosion, weeds and evaporation. As such, mulch can reduce the need for fertilizers, herbicides and water. Indeed, mulch generally retains more moisture near the soil surface than does traditional compost. This reduces volatilization from both soil and fertilizers Barden et al., 1987, p. 198-199).

One negative aspect of mulching is its relatively high cost, including both labor and the mulch itself, relegating its application to high-valued garden plants and crops. In Hawai'i, these high-valued crops include snap beans, Maui onions, green onions, and red bell peppers, the prices of which currently range from $1.69 to $4.99 per pound in the supermarket (Hawai'i Agricultural Statistics Service, 1991, p. 24, 47 and 57-59; Manoa Safeway Produce Department, personal communication).

In addition, one study has found that the absence or presence of thatch (mulch consisting only of grass) dramatically affects volatilization of ammonia and N_2O. Eight days after application of urea to a plot of Kentucky bluegrass containing a 2-inch layer of thatch, nitrogen volatilization was measured to be 39%, compared to only 5% in a plot with no thatch (Spectrum Research, Inc., 1990, p. 131). Thus, mulch and fertilizer applications should be staggered carefully in order to minimize nitrogen emissions.

One type of mulch in Hawai'i consists of simply a polyethylene plastic sheet which is spread over the soil, in particular over pineapple fields. Seeds or pineapple tops are planted in perforations in the plastic, perforations which also allow rainfall and irrigation water to reach the ground in amounts necessary for the crops' survival. In the end, there is almost complete elimination of evaporative losses, and applications of fertilizer and irrigation water can be reduced. The primary drawbacks are the cost of the plastic and the litter it produces. Plastic also emits hydrocarbon pollutants as it degrades.

In contrast, organic mulch is generally cheaper and lends itself more to net carbon uptake than to net emissions. Side benefits of mulching include:

- Reduced weed growth.
- Cooled ground surface, which helps seeds germinate.
- Increased water infiltration and retention.
- Reduced erosion.

Educating farmers on the positive environmental effects from the use of mulch can be aided by demonstrations of its application to various crops.

b. *Help expand the market for composted manure as fertilizer.*

This is the same as No. 4a under the Livestock and Manure Management section above. Composted manure can be an excellent substitute and/or supplement for chemical fertilizers, as previously described--in part since compost tends to involve fewer greenhouse gas emissions during its preparation. In addition, the nutrients in compost are released slowly to the roots of plants through microbial activity over an extended period of time, thereby reducing the potential for nutrients to leach from the soil. Unfortunately, an important drawback is the tendency for N_2O emissions generally to be higher from organic fertilizers (from farm animal or human excreta) than from mineral fertilizers per pound (Energy Information Administration, 1995, p. 89).

Thus, a combination of organic soil amendments and petroleum-based fertilizers may offer the best means for producing high-quality crops: The organic component provides good overall soil structure, and the fertilizer supplies the nutrients necessary for desired growth (EPA, 1994, p. 88). However, the proper proportions of this mixture depend on the concentration at which the positive aspects of the compost are maximized--a proportion which varies from place to place and season to season, complicating attempts to support or legislate the use of compost as a soil amendment. As a result, the various government agencies involved should simply provide as much support as possible to the market mechanisms seeking to find this balance. On the other hand, one active approach which the state can take is the taxing of all imported fertilizer (Zaleski, personal communication).

c. *Help expand production and marketing of anaerobically digested biosolids (sewage sludge) as fertilizer.*

Biosolids from animal and human waste streams which have been treated anaerobically can also be applied as fertilizer to crops and pastures. Indeed, the most common use of anaerobically digested biosolids in the world has been, and remains, as fertilizer for farm crops (Hobson and Wheatley, 1993, p.238). Digesters not only leave a sludge residue that retains high levels of nutrients, but they provide energy-generating methane as well (see Sewage Management below). Digested cattle biosolids, when used in mushroom compost, have even been found to cause better and quicker mushroom growth than does conventional compost (Hobson and Wheatley, 1993, p. 238). Furthermore, as noted earlier, diversion of biosolids from landfills preserves those landfills' methane collection systems from hydrogen sulfide fumes emitted by biosolids (Baker, personal communication).

The economics of composting operations vary widely, however, according to their location, size, the price of their compost and the number of factors figured into the analysis. The city of Los Angeles uses the windrow method of composting, and reported costs of only $5 per wet ton in the summer months in the early 1980s, during which time Los Angeles was composting up to 23% of its total sewage solids (Goldstein, 1984, p. 19). Similarly, on the mainland, composting of feedlot manure was estimated in the early 1980s to cost an average of $10 to $13 per ton of compost if the compost company worked independently, and only $7.50 to $10.50 per ton if it became partners with one or more feedlots. A net profit was generated in either case, since at the time compost was selling for $22.50 to $30 per ton, spread (Goldstein, 1984, p. 40). However, the price of compost remains in this range in Hawai'i today, while the cost of operation is undoubtedly higher than it was in the Los Angeles analysis. This has the effect of decreasing the benefit/cost ratio in Hawai'i and increasing the payback period somewhat from those elsewhere. Fortunately, the payback periods for composting facilities measured in other studies have been quite rapid (see Table 1), suggesting that such operations are likely to be profitable in Hawai'i as well.

On the other hand, composting operations in some areas have shown significantly higher costs than those in the Los Angeles study (Table 16); yet it appears that this occurs mainly where the market for the compost is limited. In general, composting operations tend to have high rates of return (Table 1)--especially the windrow method, which generally costs only about 2/3 as much per ton as does the aerated pile method (Table 16; Goldstein, 1984, p. 22).

	Land Spreading		Composting	
Capacity of Storage	32140 ft^3	41070 ft^3		
Compost Production			1,433 wt/yr	2,535 wt/yr
Land Spreading by	Contractor	Producer		
Composting Process			Forced Ventilation	Windrow Composting
Capital Cost	200,000	283,333	228,333	238,333
City Investment	100,000	141,667	114,167	119,167
Annual Operating Cost	35,500	35,167	37,833	37,500
Annual Depreciation	7,083	13,333	11,750	10,667
Other Annual Costs	6,250	8,917	7,167	7,500
Total Gross Annual Cost	48,833	57,417	56,750	55,667
Annual Revenue	3,333	3,333	13,300	23,000
Net Annual Cost	**45,500**	**54,083**	**43,367**	**32,667**
Cost/Ton of Dry Matter	**182**	**216**	**173**	**131**

Table 16. Land spreading vs. composting of sludge from a 2,200 wet ton (wt) per yr sewage treatment plant serving 15,000 people. All costs and revenues in US dollars, converted from French francs assuming six francs/dollar. All projects lose money, due to low income for finished product; windrow composting had the lowest net cost due to a private company's buying all at a low price. From Martel, 1991, p. 298.

Side benefits of land application (and composting) of anaerobically digested sludge (Goldstein, 1984, p. 40; Hobson and Wheatley, 1993, p. 228-234; Baker, personal communication) include:

- Compost is essentially free of pathogens and weed seeds.
- Odor of manure is reduced via the composting process.
- Compost is often cheaper than chemical fertilizers.
- Compost avoids emissions caused by the manufacturing of chemical fertilizers.
- Methane collection systems at landfills are spared the corrosive effects of hydrogen sulfide gas which landfilled sludge emits;
- Liquid effluent from digesters can also provide nutrient-rich irrigation for non-vegetable crops.
- Such fertilizers can be relatively slow-release, since digester bacteria leave behind the poorly-degradable constituents in the waste. This release can be

delayed further by (1) tertiary treatment of sludge, or (2) via a process wherein it is combined with urea, lime and formaldehyde at pH 4, then mixed with peat moss.

- Reduces input to landfills. (Can also be a negative aspect; see below).

- Allows feedlot owners to clean pens more routinely, thus improving cattle performance.

One possible drawback is the common practice of adding copper sulfate to pig feeds to improve animal performance. This copper, usually added to pig feed in concentrations of about 0.17 tons/yd^3, becomes concentrated to as much as 0.72 tons/yd^3 in the dry digested solids. Fortunately, the copper tends to remain as insoluble copper sulfate and is generally not taken up by plants or livestock if they are not turned out on fields immediately after sludge is spread. Millions of tons of sludge have been applied to crops and pastures in Great Britain without ill effect (Hobson and Wheatley, p. 233).

2. Improve Efficiency of Fertilizer Use (low to moderate cost, moderate benefit)

a. *Management approaches (EPA, 1995a, p. 5-53).*

i. <u>Promote improved fertilizer application rates and timing</u>. Matching fertilizer application with specific crop requirements would reduce excess fertilization. Typical fertilizer application rates vary depending upon crop type, soil conditions, fertilizer pricing, and environmental policies (Spectrum Research, 1990, p. 65). Precipitation and irrigation are also very important determining factors in the amount of volatilization which occurs after application. For example, one study has determined that irrigating shortly after fertilizer application can reduce volatilization from 36% to less than 8% (Spectrum Research, 1990, p. 118).

ii. <u>Promote improved frequency of soil testing.</u> Regular soil testing could decrease fertilizer use.

iii. <u>Promote improved placement of fertilizer.</u> Spreading fertilizer onto the surface of bare soil is actually the worst possible application method. Application either onto the plants themselves or a few inches below the soil surface can both curb nitrogen volatilization and improve plant uptake.

iv. <u>Promote reduced crop rotations.</u> Rotating crops increases CO_2 and N_2O fluxes to the atmosphere through physical disturbance to soils (Li and Cialella, 1992, p. 3).

b. Technology approaches (EPA, 1995a, p. 5-54).

i. Encourage reduced use of fertilizers containing anhydrous ammonia. N_2O is produced when fertilizer nitrogen is volatilized to the atmosphere. Studies suggest that fertilizers containing nitrogen in the form of anhydrous ammonia tend to have higher N_2O emissions than other nitrogenous fertilizers. In the U.S., anhydrous ammonia accounts for about 38% of nitrogenous fertilizer use, compared to 21% for ammonium nitrate and 11% for urea (OTA, 1991, p. 257). Use of anhydrous ammonia in Hawai'i may be less, but no specific figures are available at this time.

ii. Encourage increased use of fertilizers with slow-release coatings. The determinants of nitrogen volatilization are considered to be fertilizer type, application rate, and application method. For example, granular fertilizers tend to volatilize less than do liquid fertilizers. Release rates of granular fertilizers can then be further reduced via coatings such as sulfur or plastic, which degrade over time. These improve efficiency by releasing nitrogen at rates which approximate crop uptake. This reduces the amount of excess nitrogen which can be volatilized at any given time. Under certain conditions, application of slow-release fertilizer in the U.S. can double fertilizer efficiency, although whether overall N_2O emissions are simultaneously reduced is unclear (OTA, 1991, p. 257).

One plastic coating, isobutylene, is actually a side product of the film industry which would otherwise be added to the waste stream (Spectrum Research, 1990, p. 118). Another advantage of isobutylene is that it is released by contact with water, which causes it to release its fertilizers only during irrigation or rainfall. The tradeoff is that isobutylene-coated fertilizers tend to be more expensive then other slow-release fertilizers, and slow-release fertilizers in turn tend to be more expensive than regular fertilizers. As a result, their use in Hawai'i is mainly relegated to golf courses, ornamental plants and high-income crops. Plastic and sulfur may also be considered pollutants under certain conditions (Dave Klawitter, personal communication).

Another type of slow-release fertilizer is sulfur-coated urea, which is often preferred in wetter areas (Spectrum Research, 1990, p. 118). KNO_3 is a key ingredient of yet another class of slow-release fertilizers which tend to work better in drier areas (Spectrum Research, 1990, p. 117). All of these fertilizers have properties which recommend them for further study regarding their applicability to agricultural and recreational uses in Hawai'i.

iii. Promote increased application of nitrification inhibitors to fertilizer. A wide range of additives curtail nitrification processes in the soil around applied fertilizers, in some cases increasing the efficiency of nitrogen uptake by plants by some 30% (OTA, 1991, p. 257).

iv. Promote increased application of hormones to grasses of recreational areas such as golf courses and sports fields. Certain hormones can also be added to fertilizers to stimulate growth, mainly of turfgrass. As a result, the grass becomes more resistant to the stress placed on it by recreational activities. The savings in fertilizer use have made these biostimulant fertilizers economically viable in many areas of the developed world, even for short-term consumers. Grasses also become more resistant to diseases (Schmidt, 1990, p. 1-4).

v. Promote planting of grasses and crops which require less fertilization. On golf courses, turfgrass is the predominant grass due to its aesthetics, reliability and resilience. Alternatives do exist, however. One alternative to turfgrass could be the use of zoysiagrass. Compared to typical turfgrass, zoysiagrass is drought-resistant, salt-tolerant and requires significantly less fertilizer. It lacks some of the aesthetics of turfgrass due largely to its coarser texture, but when planted in the roughs alongside fairways, zoysiagrass would help the industry to further reduce its greenhouse gas emissions (Duble, 1996, p. 1-3.). Rye grass and fescue also tend to have fewer fertilizer and pesticide needs than do the bluegrasses (Klein, 1990, p. 28).

Various options discussed in this section can be combined into a system of "cultural practices" which maximize the efficiency of applied fertilizer. The Hapuna Golf course on the Big Island is one example of a golf course which incorporates such cultural practices. First of all, the superintendent fertilizes only about once every three months, at which time approximately half a pound of slow-release fertilizer is applied every 1,000 square feet. Quick-release fertilizers are used only for greens. The course superintendent plans to further reduce this application amount to about 1/3 of a pound in the future, by adding a variety of bacteria to the fertilizer (Milton Nakagawa, personal communication).

As can be seen in the paragraph above, most—if not all—golf courses, incorporate a mixture of slow-release and quick-release fertilizers. Pending further study, it may be possible to recommend that a minimum of 50% of the fertilizers used on golf courses in Hawai'i should be slow-release varieties (Dave Klawitter, personal communication). Superintendents can also be educated on the effects of excess nitrogen-rich fertilizers and volatilization. In some states, the superintendents are required to get training and certification acknowledging that they understand the effects of overfertilization and methods to mitigate this practice. Such a requirement would likely provide much of the incentive necessary for improved maintenance practices at Hawai'i's golf courses.

The fertilizers and additives discussed here do not exhaust the range of existing varieties, but should be sufficient to demonstrate the merits of further study and experimentation with these in Hawai'i. Golf courses are an important component of the state's economic health, and can serve as attractive showcases for careful management of resources and minimized emissions. Incorporating any of the fertilizers or amendments suggested above could thus have positive repercussions beyond the reduction of nitrogen volatilization alone.

3. Promote Planting of Cover Crops which Capture Nitrogen (low to moderate cost, low to moderate benefit)

Nitrogen-fixing crops can substantially augment nitrogen inputs into agricultural systems via absorption into soil. Nitrogen fixation can decrease emissions not only of N_2O, but CO_2 and CH_4 as well (Johnson and Henderson, 1995, p. 138), and can also benefit overall crop production. Refer to the third paragraph of the agroforestry segment (p.78) for further discussion of this concept.

4. Promote Improved Soil Management (low to moderate cost, low benefit)

It should be noted that the following discussion is also applicable to parts of the land use management and manure management sections.

Soils are significant reservoirs of carbon, and various conservation practices can be employed to reduce their greenhouse gas emissions. Nitrogen is particularly critical because it is both required by plants in relatively large amounts and subject to loss via leaching, volatilization, and denitrification. A sustainable farm relies principally upon organic nitrogen sources, especially legumes and animal manures. Synthetic, soluble nitrogen sources should be discouraged, where possible, since they require non-renewable petrochemicals in their manufacture and may have negative effects on soil physical and biological properties (Andrews et al., 1990, p. 283-284).

Central O'ahu has a potential problem regarding legumes, however. Soybeans and most other legumes are not very acid-tolerant, and farmers in this area are currently increasing their applications of lime and other alkali sources to raise the pH of Hawai'i's naturally acidic soils. Unfortunately, it was recently discovered that a large lens of nitrate currently resides in the upper 35-40 feet below the surface in this area, a lens which would be liberated to enter the island's main aquifer if the soil's pH rises above a certain level. Although some deep-rooted legume crops such as the calliandra tree can extract nitrate from this depth, most legumes are shallow-rooted and their cultivation could actually worsen O'ahu's nitrogen problems rather than improve them. Crops extracting nitrogen from the soil also forego the more difficult process of fixing nitrogen from the air, so their net benefit in terms of greenhouse gas emissions is negated Uehara, personal communication). This dilemma deserves much greater scrutiny than it has received to date.

The following management practices promote soil carbon retention (Dixon et al., 1993, p. 563):

a. *Promote and undertake afforestation and removal of marginal lands from agricultural production (see section on Land Use Management below).*

b. *Promote reduction of crop tillage intensity. Reducing the amount of tilling in fields can result in increased retention of soil and organic carbon, and thus reduced CO_2 and possibly N_2O emissions*
The degree to which the change in tillage intensity affects carbon sequestration depends on crop type; but according to modeling results, the effect of such changes on CO_2 emissions is much greater than on N_2O emissions (Li and Cialella, 1992, p. 1-3). The tradeoff is that these tillage practices tend to improve the habitat for crop pests, increasing the need to apply pesticides (OTA, 1991, p. 253). Such practices may also reduce the uptake of nitrogen by crops, increasing the need for fertilizers, and thus negating any reduced N_2O emissions (Li, 1995, p. 105-106). Currently, about 27% of cultivated land in the U.S. employs reduced tillage methods, and 10% to 14% of the total acreage of corn, soybeans and wheat in the country were managed with no tillage at all in 1992 (Hedger, 1996, p. 28).

5. Indirect Approaches (low cost, indeterminate benefit)

In addition to the above, the following measures would provide more indirect encouragement to reduced emissions from agriculture in general and fertilizer use in particular:

a. *Keep and compile better records of agriculture practices.* The types of crops, area under cultivation and yields of each, amounts of fertilizer and burning employed, and related data are necessary for better planning and modeling. The Department of Agriculture is not yet empowered to collect such information (State of Hawai'i, 1992, p. 102).

b. *Modify land tenure to allow longer-term leases, thus giving better encouragement to farmers to spend money on long-term conservation and emissions reduction practices* (IPCC, 1991, p. 191; Zaleski, personal communication).

c. *Develop a policy to manage and possibly regulate fertilizer use statewide.*

At least as recently as 1992, the state has not managed or regulated the use of fertilizers in any way. The Department of Health (DOH) has, however, included mitigation of potential fertilizer impacts on drinking water resources among its twelve conditions for golf course development. Developers and owners must monitor runoff and groundwater for fertilizer contamination, waterproof buildings where fertilizers are stored and surround them with protective berms, implement "best management practices" for application and monitoring of fertilizers, and irrigate using reclaimed water where possible (State of Hawai'i, 1992, p. 22 and D-1 to D-3).

Few states have authored legislation addressing fertilizer use in recent years. One exception is Minnesota, which established a Nitrogen Fertilizer Task Force to study the effects of nitrogen fertilizer use on water resources in order to help the state develop best management practices, a fertilizer management plan, and nitrogen fertilizer use regulations (OTA, 1991, p. 330). There is clearly room for improvement in this regard in Hawai'i, not for golf courses alone but for all large-scale fertilizer users in the state.

D. Land Use Management

For the U.S. as a whole, it is estimated that forests sequester some 99 million tons of carbon per year, or about 2.5 to 5 tons/acre/yr. In recent decades this sequestration has been increasing annually by about 0.8%, as a portion of cropland is abandoned and formerly-abandoned land moves toward mature forest status (Energy Information Administration, 1995, p. 69). On the other hand, when forest land is cleared for agriculture, a large net emission of carbon to the atmosphere results. Even conversion of pasture or grassland to cropland loses approximately 30% of the carbon in place at the time of conversion. Similar trends are apparent for N_2O (Energy Information Administration, 1995, p. 69 and 73).

Forest plantations and forest restoration offer what appear to be the most attractive means to mitigate global warming. This is because a) forests have the potential to sequester large amounts of carbon, b) the technology for establishing large areas of additional forests has been tried and proven, c) forests have a number of environmental benefits aside from carbon sequestration, and d) most studies indicate that the costs of carbon sequestration using forests are relatively modest (Sedjo et al., 1994, p. 2). To make forest restoration reasonably permanent in Hawai'i, however, would likely require changing the zoning classification of some land from agricultural to conservation status.

The implementation costs of land use management are reported in various ways, but they generally include site preparation, stock costs (i.e., equipment for planting, propagation, packing, storage, and transportation), labor and supervision. Other considerations include the cost of land, tending and maintenance costs (Winjum et al., 1993, p. 243).

1. Support Establishment Of Tree Plantations (low cost, high benefit)

a. *Increase the productivity of existing plantations.*

Tree plantations provide a relatively easy, low-cost method of sequestering carbon. Improvements in sequestration can occur either through converting other agricultural land to tree plantations, or by increasing the productivity of existing plantations. One way to accomplish the latter is to plant genetically-improved trees. For example, it has been estimated that planting genetically-improved loblolly pines (*Pinus taeda*) can produce up to 11 tons C/acre/yr over a 35-year period, while hybrid cottonwoods can exceed 27 tons C/acre/yr (OTA, 1991, p. 209 and 214). Such short-rotation woody crops could offset 3% to 5% of current U.S. CO_2 emissions, even assuming no technology advancements such as higher growth rates or higher energy conversion efficiencies. It is estimated that such technology advancements could ultimately offset up to 35% of current U.S. CO_2 emissions (OTA, 1991, p. 215). A host of studies have suggested relatively low carbon sequestering costs through tree planting, in many cases under $10 per ton and rarely over $30 per ton (see Table 16; Sedjo et al., 1994, p. 5).

b. *Encourage conversion of abandoned agricultural land to tree plantations.*

Even as early as 1992, less than 25% of the land classified as agricultural in the state was actually under cultivation (State of Hawai'i, 1992, p. 97)—a percentage likely to be far lower today. In 1993, the State of Hawai'i Department of Land and Natural Resources (DLNR) hired a consulting firm to evaluate the potential of reforesting abandoned sugarcane lands. The firm predicted that commercial forestry in Hawai'i could offer returns of up to 19 percent. The state responded by mailing a prospectus to possible investors worldwide (Davis, 1994, p. 42). Among the companies which have made use of this are Hawai'i's energy utilities, who get CO_2 credits for planting trees to offset the greenhouse gases emitted by their facilities (Masaki, personal communication).

At least two state laws direct DLNR's afforestation efforts. LNR 172 encourages DLNR to use DLNR lands in economic ways, such as by planting high-value hardwoods or eucalyptus. LNR 402 guides DLNR's efforts to stabilize soil and revegetate denuded land with plantings. However, in practice a lack of funds means that these saplings are generally planted with a handful of fertilizer, then left on their own with no supervision (Masaki, personal communication).

Currently, DLNR also conducts a Forest Stewardship program in conjunction with the U.S. Natural Resources Conservation Service. This program has established partnerships with private landowners for such actions as tree planting on former sugarcane lands, providing the state with about $10,000 per year for this activity.

Among other accomplishments, this program has led to the Bishop Estate establishing tree plantations on about 22,000 acres of former sugarcane lands in the Big Island's Hamakua region (Masaki, personal communication; Ayers, personal communication).

c. *Landowners with forested lands should be provided tax incentives, even when such forests are not predominantly native.*

State and county governments can also provide more direct incentives to reforestation. One precedent is the lower property tax which already exists for landowners on the Big Island with native trees on their land. Previous to this incentive, many of these landowners would run livestock on their property in order to qualify for lower pasture or agricultural taxes (Ayers, personal communication). Kaua'i has a more proactive law, which provides tree plantations with a tax break until such time as they are harvested. It thus seems beneficial to provide landowners with land in forest with *some* tax incentives, even when such forests are not predominantly native. Such afforestation should not, however, come at the expense of native forest. Instead, managed forests should be placed on available pasture and cropland, marginal land and/or degraded land (OTA, 1991, p. 226).

2. Promote Agroforestry (low cost, moderate to high benefit)

Particularly in temperate areas of the world, many countries are now looking at agroforestry as a method to provide additional economic stability, increase efficiency of land use, and--incidentally--reduce greenhouse gas emissions (IPCC, 1991, p. 89).

Agroforestry is defined as the deliberate growing of woody perennials and agricultural crops--plus possibly the raising of animals--in the same area, either in spatial combination or in sequence. An example of agroforesty would be the alternating of corn and beans on a plot of land, bordered by a windbreak consisting of fruit trees, with chickens also present. Characteristics of agroforestry include significant interaction between woody and non-woody components, either through ecological or economic means (or both), as well as an increase in carbon uptake per area.

Where properly implemented, cultivation of woody perennials sequesters additional carbon not only in the plants themselves, but also in the soils due to increased shading, reduced plowing, maintenance of high fertility and the buildup of humus on the soil surface. Trees and other woody perennial crops reach much deeper and lock carbon out of the atmosphere for much longer periods than do annual crops, and N_2O and CO_2 emissions can also be mitigated by reduced fertilizer applications and fossil fuel use (OTA, 1991, p. 258). Agroforestry must be adaptable to the local environment, be well-designed, be effectively managed, and meet the current needs of farmers in order to accomplish its full potential (Blando, 1989, p. 34).

a. Promote the planting of nitrogen-fixing trees along with crops to act as windbreaks, fertilizer supplements, and eventually sources of bioenergy or lumber.

Nitrogen-fixing crops (e.g., soybeans, peas and alfalfa) and trees are of particular interest in agroforestry systems, since these leguminous plants extract nitrogen from the atmosphere or pore spaces in the soil and convert it into a form usable by themselves and other plants. Thus, legumes not only require less fertilizer than do other crops, but they also leave nitrogen in the soil for use by other plants, improving the long-term productivity of farms. Nitrogen-fixing trees in agroforestry systems are used largely for fodder, fuelwood and soil improvement (Blando, 1989, p. 60-62). Unfortunately, little information exists as to the degree to which legumes planted in conjunction or in rotation with other crops actually reduce fertilizer requirements (OTA, 1991, p. 257).

It should be noted that at least one source has argued against promotion of nitrogen fixation, since this process helps convert N_2 gas to N_2O. Thus, from a restricted viewpoint there is essentially no difference in the greenhouse effect caused by fertilizers and by nitrogen-fixing plants (Beardsley, 1997). Yet nitrogen fixation should still be preferred to fertilizer application, in particular to the degree that fixation avoids the fossil fuel emissions caused by the production, transportation and spreading of fertilizers.

Some recent studies estimating and comparing the costs of sequestering carbon through tropical, monoculture forest plantations vs. those of tropical agroforestry are listed below (Table 17):

Author	Forest Plantations	Agroforestry Plantations
Andrasko (1991)	\$3-6	\$3-5
Dixon et al. (1993)	\$6-60	\$4-16
Houghton et al. (1991)	\$4-37	\$3-12

Table 17. Costs (per ton of carbon sequestered) for establishing tropical forest and agroforestry plantations. From Sedjo et al., 1994, p. 5.

The wide ranges in these values demonstrate both the difficulty of comprehensively assessing costs and the range of values resulting from different plantation sizes and locations (Sedjo et al., pp, 5-7). Nevertheless, these studies agree that costs are generally lower for agroforestry plantations than for monoculture forest plantations. Since the measurable benefits of agroforestry are likely to be greater as well, it should receive priority treatment in any government promotions.

Side benefits of promoting agroforestry include (Blando, 1989, p. 29-30):

- Ability to control erosion, thereby reducing losses of soil organic matter and nutrients.

- Agricultural systems maintain more favorable soil physical properties than using traditional agriculture, through a combination of organic matter maintenance and tree root effects. This offers opportunities to augment soil water availability to crops.

- Can lead to more closed nutrient cycling, and so to more efficient usage of nutrients.

- Can be a useful component of systems for reclamation of degraded soils.

- Reduces area required for agriculture.

3. Promote Urban Tree Planting (low cost, low to moderate benefits)

In Hawai'i, urban trees contribute to atmospheric carbon reduction in two ways: By directly sequestering carbon in trees and soils, and by reducing energy requirements for cooling buildings. Trees cool urban heat islands by lowering air temperatures through evapotranspirational cooling and by direct shading of buildings and paved surfaces (Sedjo et al., 1994, p. 16).

The EPA has proposed the following tasks regarding urban tree planting--tasks which should be readily implementable in Hawai'i (EPA, 1992, p. xxvi-xxvii):

a. *Undertake (or expand) community-wide programs for shade tree planting. These can consist of volunteer programs in conjunction with community groups and public education (but see Disadvantages below).*

b. *Promote energy conservation activities by providing information on landscaping designs.*

   Pertinent information should be directed at retailers of building materials and trees, through federal and state forestry departments, city land use management personnel and utilities.

c. *Provide incentives for developers to design well-landscaped buildings and communities.*

Assuming each tree costs $5 to $25 to plant and two years of follow-up care, scientists from the Lawrence Berkeley Laboratory estimated the benefits of conserved energy and sequestered carbon to be $6 to $26 per ton, with temperature reductions of as much as 9^{o} F and air-conditioning reductions of 10% to 50% (EPA, 1992, p. 32; Sedjo et al., 1994, p. 17). U.S. Forest Service research suggests that when the economic value of non-demand-side management benefits of tree planting (listed below under side benefits) are monetized, total benefits can be two to three times greater than costs for tree planting and care (Sedjo et al., 1994, p. 20). One project which has been carried out began in Tuscon, Arizona in 1993, with the goal of planting 500,000 desert-adapted trees by 1996. The projected costs and benefits over a 35-year period for this project are displayed in Figure 16. Costs for the Tuscon project include planting, pruning, tree removal, and irrigation water. Benefits accounted for include cooling energy savings (97%) and avoided dust and stormwater runoff costs. The benefit-cost ratio and internal rate of return for this project were estimated to be 2.6 and 7.1, respectively (EPA, 1992, p. 41). The carbon dioxide offsets of a nationwide urban tree planting program are estimated to be on the order of 0.7% of 1987 U.S. emissions by 2015 (OTA, 1991, p. 216).

Actual avoided emissions and carbon storage by newly-planted city trees will be limited by the amount and location of growing space suitable for tree planting, tree survival and growth rates, degree (and cost) of maintenance, building characteristics, and climate (OTA, 1991, p. 216; Sedjo et al., 1994, p. 18; EPA, 1992, p. 27 and 60).

Side benefits of promoting urban tree planting:

- Improved aesthetics and property values
- Reduced noise
- Removal of air pollutants
- Reduced urban runoff and, in some cases, erosion
- Reduced wind speed
- Increased habitat for birds and other animals

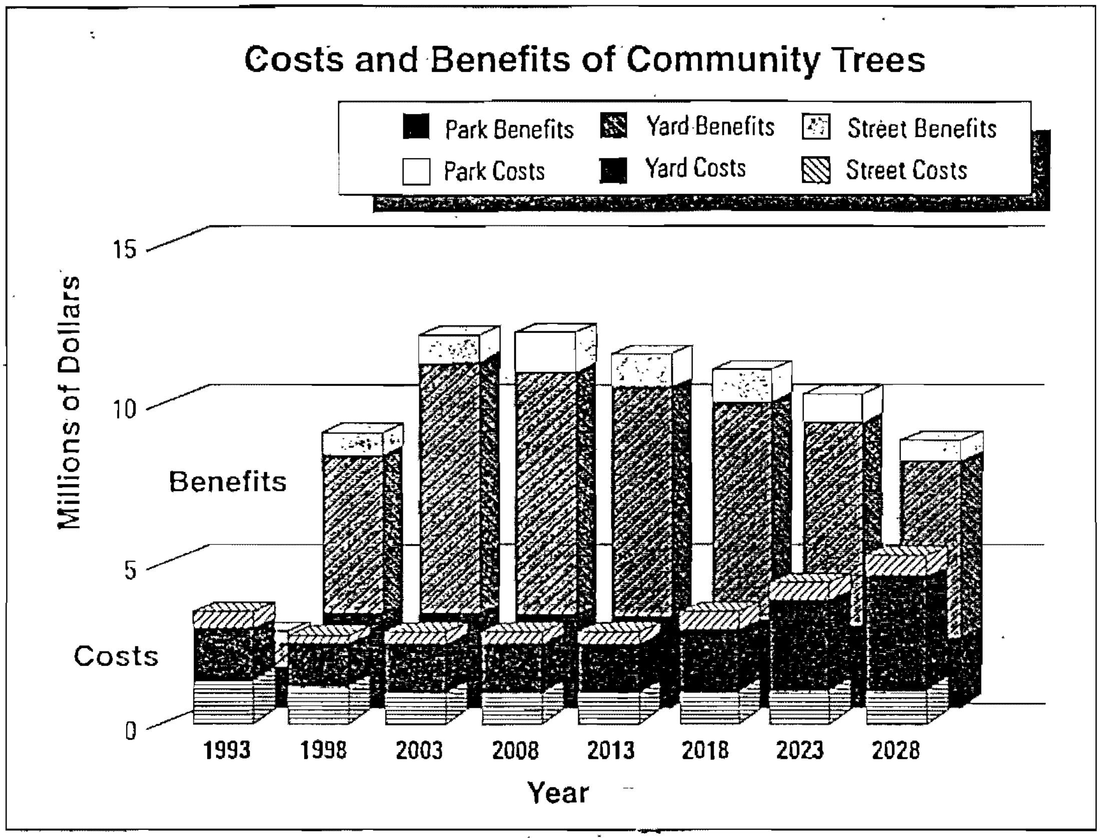


Figure 16. Projected costs and benefits of a reforestation program for Tucson, Arizona. Note the high benefits associated with tree planting in residential yards. From EPA, p. xxv.

Disadvantages:

- Increased solid waste costs for pruning and removal of dead trees.
- Increased solid waste amounts in landfills if disposed trees are not mulched or otherwise recycled.
- A tendency for volunteer efforts in public areas to be limited to planting of trees, with maintenance typically left to city workers.

Since 1990 in Hawai'i, DLNR has helped administer at least two separate urban tree planting programs. The America the Beautiful Program and the Stewardship Incentive Program together supply approximately $50,000 per year to the state and counties, which then issue subgrants to communities and landowners on a cost-sharing basis. Any request for funds, which usually cover half of the project's cost, must pass through a committee with representatives of both the public and private interests. This program has managed an average of fifteen projects per year, primarily for community beautification. The National Arbor Day Foundation, a non-profit organization on the mainland, also grants about $2 per capita to communities that qualify for urban planting project grants (Ayers, personal communication; Hedger, 1996, p. 65). There are additional programs to get involved in. For example, the U.S. Cool Communities program has begun encouraging the planting of shade trees particularly in residential areas, in order to improve home efficiency and act as a carbon sink (Hedger, 1996, p. 64).

4. Improve Forest Management (low to moderate cost, low to moderate benefit)

a. Increase productivity of managed forests.

Traditional forest management is directed at increasing both the volume and the quality of forest resources. Methods to increase forest productivity include (1) either stocking additional trees to achieve optimal forest density or thinning trees to decrease competition, (2) selecting genetically superior tree strains, and (3) protecting trees from fire, insects and disease (Sedjo et al., 1994, p. 13).

Many states have long had forest management programs of one sort or another, and some are now establishing tree-planting programs in response to global warming and other concerns. For example, a 1990 Executive Order passed in New Jersey calls for maximizing the number of trees in the state, and in response a program has been put in place there to replace all trees lost as a result of state construction activities (OTA, 1991, p. 330).

Economically, the calculated benefit of carbon sequestered by active forest management across U.S. forest regions is estimated to range from $9 to $27 per ton of carbon, with the range for tree planting alone being $5.5 to $22 per ton of carbon (Winjum et al., 1993, p. 251). Increasing the density of existing forests by underplanting (Method 1 above) is estimated to cost, on average, approximately

50% to 75% of the costs of establishing a new plantation, not including the price of land purchase (IPCC, 1991, p. 93).

b. *Continue to support the governor's initiative calling for a comprehensive examination of Hawai'i's forests, expanding the focus to include greenhouse gas sequestration.*

In Hawai'i, DLNR has recognized both the environmental and economic value of trees and has made an effort to promote forestry management on state and private lands while maintaining habitat for forest plants and animals. Different species of *Eucalyptus* in particular have shown promising results for short-rotation (5 to 8 years) management in Hawai'i (Whitesell et. al., 1992, p. ii). This option was given a boost in January of this year, when the governor declared an initiative calling for a comprehensive examination of the economic potential of Hawai'i's forests. This initiative focused primarily on economic development but also on education, marketing, and a survey of available timber (Ayers, 1997).

c. *Land destined for conversion to non-forest uses, and any land for which the final use is uncertain, should be kept as managed forest indefinitely or until the need for clearing arises.*

In addition to more fully managing existing forests and converting unused agricultural land to forest, attention should be paid to preserving forest which is destined for conversion to non-forest uses such as agriculture and residential development. Indeed, any unused land for which the final use is uncertain should be managed as forest land indefinitely or until the need for clearing arises. This is easier to do for public than for private land, but incentives similar to those for the urban tree planting noted above would improve the economic considerations for landowners.

E. Crop Burning and Bioenergy Crops

Emissions from the burning of crop residues have been decreasing both nationwide and in Hawai'i over the last decade (Energy Information Administration, 1995, p. 42). Since the carbon content of crop residue varies from 40 to 50% of dry matter, burning of these residues emits carbon into the air. Most of this carbon is in the form of carbon dioxide, but varying levels of CO and methane are also produced. A certain amount of N_2O is produced as well. In some states today, such burning is now legally banned (Energy Information Administration, 1995, p. 43).

In Hawai'i, about 35% of sugarcane residue ("crop waste") has traditionally been burned directly in the fields, with the remainder ("bagasse") going to generate power for sugar mills and to sell power to the county utilities. This should be encouraged since it avoids burning imported oil and emitting associated greenhouse gases. While this topic moves close to the energy sector to be covered by DBEDT, it is important to consider from the non-energy perspective as well.

In Hawai'i, both sugarcane and pineapple production have dropped precipitously from their levels of just five years ago. What bagasse is not collected and burned in the mills is often mulched to serve as fertilizer for the next crop (Whalen, personal communication). Since some bagasse is still burned on the fields, however, the decline of this industry has a positive impact on greenhouse gas emissions from agricultural fields, since other crop residues are generally not burned to the same extent as sugarcane and pineapple residues. However, this also has negative impacts on the mills which were designed to burn such bagasse. Since 1992, almost half of the state's biomass energy conversion facilities have closed down, although the Waialua Sugar Mill recently began part-time operations again (Greer, 1997, p. 4; Harder, personal communication). These mills could be revived by using different biomass sources or a different cultivar of sugarcane (local agronomists are currently experimenting with a variety of cane which can be harvested in 14-16 months rather than every two years), but at present the selection is rather limited (Whalen, personal communication).

In Pai'a, Maui, a gasification plant—which converts biomass to biogas—is currently being upgraded to process 50 tons of dry biomass per day, with plans to eventually accommodate 100 tons per day (Parsons Brinckerhoff Quade and Douglas, Inc., 1995, p. 7-1 to 7-5; Kinoshita and Trenka, 1994, p. 10). Eventually, the plant owners, Hawaiian Commercial & Sugar Company (HC&S), hope to connect a generator to the facility and provide 5 MW of electricity to the island's electric grid, but at present the biogas is simply being flared. The minimum $10 million price tag ($2000 per kilowatt) for this gas turbine-generator, which would be the first of its kind, has apparently frightened away all investors to date (Masutani, personal communication).

An even more ambitious project, a 20 MW gasification plant in Olokele, Kaua'i, is even more tentative at present in spite of the probability that the economy of scale would make it more profitable than the Pai'a plant. In large part, this uncertainty is due to the fact that the existing gasification plant would need to be almost entirely replaced by a larger plant using relatively untested technology. As a result, both plants would require government support to be economically feasible, and costs would be reduced considerably if the technology was tested elsewhere first (Masutani, personal communication; Kinoshita, personal communication).

Yet another project—for the Pioneer Mill in Lahaina, Maui—has considered combining forces with the local wastewater treatment facility. The mill would use treated wastewater to irrigate its "energy cane," which would be gasified to produce power and the sugar fermented to produce ethanol. Biogas from digested sewage sludge, together with food waste and green waste from the community, would also be fed into the gasifier, which would supply electricity back into the town (Figure 17). In spite of the sugarcane's high productivity (125 wet tons per acre per year), fairly high costs ($22 per wet ton) combined

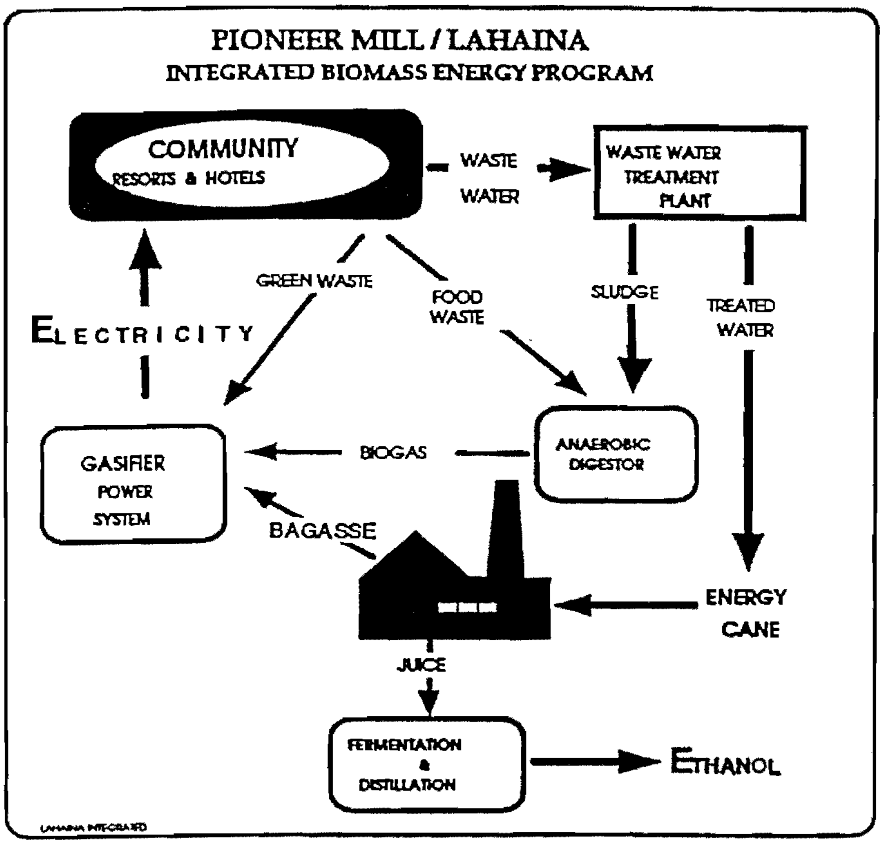


Figure 17. Diagram of proposed integrated biomass gasification project at Pioneer Mill, Lahaina, Maui. Project has been postponed indefinitely. From PICHTR, 1995, p. iii.

with high taxes (see page 1) doomed the project to failure, with an average projected loss of over $215,000 per year (PICHTR, 1995, p. iv to v).

A relevant technology which is remote yet promising is that of the fuel cell, which converts the chemical energy of a fuel directly to heat and electricity. Since fuel cells operate at a lower temperature than typical gasification plants, they are more efficient and produce less NO_X. However, the largest fuel cell tested to date generated only 200 kW (Masutani, personal communication; EPA, 1993b, p. 4-19).

Although the relatively healthy sugar industry on Maui appears to be able to provide a fairly stable biomass source for the Pai'a plant, the decline of the sugar industry elsewhere in Hawai'i has left the operators of other mills scavenging for biomass from other sources. These include landscaping green waste, used cooking oil from restaurants, and used diesel oil. The Ololeke mill mentioned above has even considered using demolition and construction debris from Hurricane Iniki as a short-term power source (Matsutani, personal communication, Kinoshita, personal communication). It has been pointed out by several sources that sugarcane cultivars and agronomic practices could be engineered to maximize biomass rather than sugar yield for a plant which already produces biomass at a very high rate. Other crops can be grown for their energy content as well. A 1995 study concluded that the biomass alternatives to sugarcane which offer the most potential to Hawai'i were *Eucalyptus* and *Leucaena* trees and napiergrass (*Pennisetum purpureum*). Eucalyptus is particularly promising since eucalyptus plantations covered 85,000 acres in Hawai'i in 1993. On the other hand, sugarcane can also be fermented to produce such liquid fuels as ethanol, a benefit not offered by most other biomass sources (Parsons Brinckerhoff Quade and Douglas, Inc., 1995, p. 7-5).

The Wai'alua Sugar Mill on O'ahu—which recently began burning wood chips and waste car oil to produce 8 net MW of power (*Honolulu Advertiser*, March 11, 1997, p. B3)—has considered using napiergrass grown nearby as a fuel source, but even this is considered feasible only with a government subsidy. Along the Hamakua coast of the Big Island, the Bishop Estate has committed some 22,000 acres to growing trees destined to be chipped and sold as fuel on a 5-7 year rotation (Kinoshita, personal communication; Ayers, personal communication). But the long growing time of such trees suggests that large areas of land in the state would have to be set aside for biomass growing in order to provide sufficient year-round fuel for even one 5 MW plant.

Some chipping was being carried out on state land until fairly recently. At present, DLNR has a rather large tract of non-native forest it would like to chip for power at the Wai'akea Forest Reserve, but has not yet found a good enough price for the trees (Ayers, personal communication). In the long term, this may be good in that it sequesters more carbon for a longer period, while increasing the ultimate value of the trees.

The cost of producing such biomass sources varies considerably from place to place, with most estimates in Hawai'i ranging from $30 to nearly $100 per dry ton. An estimate of benefits and costs associated with cultivation of various bioenergy crops in Hawai'i is shown in Table 18.

Crop (Rotation)	Commercial Yield (tons/net acre/yr)	Production Cost ($/net acre/yr)	Value, Replacing #2 Oil at $32/bbl ($)
Unirrigated			
Sugarcane (2 year)	12	1,075	768
Napiergrass (4 year)	9 to 15	800	576 to 960
***Eucalyptus urrophyla* (5 year)**	6 to 10	633 to 679	384 to 640
Irrigated			
Sugarcane (2 year)	16	1,190	1,024
Leucaena K636 (5 year)	10	1,028	640
Napiergrass (4 year)	20	1,059 to 1305	1,280
Sweet sorghum (2-4 year)	17 to 21	1,333	1,088 to 1,333
Eucalyptus (5-7 year)	10 to 12	1,400	640 to 768

Table 18. Estimated costs and benefits of commercial biomass production for various crops grown in Hawai'i. One ton of biomass is considered equivalent to two barrels (bbl) of oil. From Osgood and Dudley, 1993, p. 38; Parsons Brinckerhoff Quade and Douglas, Inc., 1995, pp. 7-18 and 7-19, and Egged, pers. comm.

As can be seen in this table, on a per-acre basis, none of these crops appear to be cost-effective at this time. The crops most closely approaching profitability in Hawai'i are probably napiergrass, sweet sorghum, unirrigated eucalyptus and irrigated sugarcane, and research into more productive cultivars is ongoing (Osgood and Dudley, 1993, p. 5; Parsons Brinckerhoff Quade and Douglas, Inc., 1995, p. 7-19).

With the preceding in mind, the following measures can be recommended for reducing emissions from crop burning:

1. **Encourage Planting of Crops which do not Require Burning as do Sugarcane and Pineapple (low cost, moderate to high benefit)**

2. **Promote Biomass-to-Energy Plants, Especially Those Utilizing Crops Grown Expressly for that Purpose (high cost, high benefit)**

If experimental plantations are initiated, they should be located as close as possible to bioconversion plants in order to reduce both costs and emissions resulting from transportation.

3. **Study and Promote Bioenergy Plantations (low to moderate cost, moderate benefit)**

a. *Encourage planting of sugarcane cultivars, napiergrass and other fast-growing biomass crops.*

b. *Encourage agronomic practices which maximize biomass.*

4. Study and Promote Plowing Crop Waste Under Rather Than Burning It (low cost, low to moderate benefit)

F. Municipal Sewage Management

Treatment of wastewater produces both effluent and sludge (biosolids), both of which in turn produce methane and CO_2. Emission of CO_2 is largely unavoidable (although see # 4 below), but methane emission can be reduced significantly—albeit at a not immodest price. Methods to reduce emissions from effluent and sludge, or to make these products perform work which displaces fossil fuel use, are addressed in this section.

1. Use Recovered Methane at Sewage Treatment Plants (moderate cost, moderate benefit)

Wastewater treatment can be either aerobic or anaerobic, although aerobic treatment also generally involves anaerobic processing of the resulting sludge, and--in the case of secondary treatment plants--vice versa. Aerobic treatment tends to require less energy to operate and lower nutrient additions, and produces less sludge; however, anaerobic treatment generally is more efficient, adapts to a wider volumetric load range (Table 19), and—most importantly for this report—converts 40% to 60% of the emitted carbon into methane rather than CO_2 (see Table 7). Although this methane is reconverted to CO_2 if and when it is combusted, in the process it can be used to power a significant percentage of the sewage treatment system and air conditioning, and—if refined into a liquid—can be used to fuel vehicles (State of Hawai'i, 1984, p. 43; EPA, 1995b, p. 54).

	Anaerobic Lagoon	Anaerobic Digestion	Activated Sludge	Trickling Filter
Area Required	Large	Medium	Small	Small
Volumetric Loading Range ($lb\ BOD_5/ft^3/day$)	0.7 to 1.3	16 to 85	32 to 80	16 to 130
Efficiency (% BOD_5 Reduction)	50% to 85%	65 to 95%	40 to 85%	85 to 95%
Shock Load Sensitivity	Low	High	Low	Low
Nutrient Requirement	Low	High	Medium	Low
Energy Costs	Low-High	High	Medium	Very Low
Biogas Production	Yes	Yes	No	Yes
Sludge Production	Low	High	Medium	Low

Table 19. Pros and cons of various wastewater treatment processes. From State of Hawai'i, 1984, p. 31.

Furthermore, while solids must be retained longer in anaerobic reactors due to slower biodegradation rates, the necessary volume of the reactor vessel is smaller due lower volumes of solids (due in turn to anaerobic bacteria devoting most of their energy to producing methane). Perhaps the main negative factors regarding anaerobic systems are (1) the fact that anaerobic reactors cost about 10% more than do aerobic reactors, and (2) in situations where secondary treatment is required, anaerobically digested effluent generally requires further treatment before it can be discharged into receiving waters. This process usually involves either activated sludge or trickling filter methods, both of which are aerobic (Table 19; State of Hawai'i, 1984, p. 28-29, 33, 45 and 49).

As noted above, while activated sludge treatment is more efficient, its high energy costs (Table 19) make it more expensive than trickling filter treatment. This higher cost can be offset somewhat by reusing methane generated by the anaerobic phase(s) of treatment. This has a large impact on overall operating costs, since most of the energy used in a conventional wastewater plant goes to anaerobic treatment (State of Hawai'i, 1984, p. 28).

Gas produced by anaerobic digestion of wastewater—or of the removed sludge—is about 2/3 methane and 1/3 CO_2, with small amounts of other gases. The average heat value of this gas is about 600 BTU/ft^3, somewhat higher than the 500 BTU/ft^3 recoverable from typical landfill gas. Although 1991 costs of biogas energy recovery from sewage in the U.S. averaged about $1.10 per ton of wet waste and between $11 and $27.50 per ton of methane, the payback period has been generally short, typically less than six years (IPCC, 1991, p. 116; EPA, 1995b, p. 63).

Use of recovered methane to power sewage treatment is already being carried out in Hawai'i Kai, a process which has turned a profit in recent years (Kennedy/Jenks/ Chilton, Inc., 1990, p. 2.5). At the Kailua Wastewater Treatment Plant, sludge gas has been used to run two gas-engine generators, and also to furnish heat to the primary sludge digester tank. A 1990 benefit/cost analysis of methane use at this secondary treatment plant concluded that methane production at the plant could only supply 25% of the plant's total power needs--a percentage which would only rise to 41% even as late as 2007. In spite of this, the study found that any methane-powered generator supplying 70 kW or more to the plant would pay for itself in less than nine years—even when environmental externalities and costs of H_2S scrubbing were figured in—and would avoid emission of significant amounts of methane by converting it to CO_2 (Kennedy/Jenks/Chilton, Inc., 1990, p. 1.1, 2.5 and 3.4, and Tables 2-4 and 3-2). Unfortunately, the exact tonnage of avoided methane remains uncertain, since the authors of this study concluded that avoided emissions from this one plant alone would equal more than all WWTPs in the entire state actually emitted in 1994 (State of Hawai'i, 1997b, p. 2-1). Although further study is obviously necessary before the overall avoided methane emissions of various waste treatment options in Hawai'i can be assessed, it appears that each WWTP converting to anaerobic treatment and/or reusing its biogas could avoid between 25% and 75% of its energy-related greenhouse gas emissions.

As with landfill gas, the state feels that sale of sewage biogas offsite cannot be done cost-effectively in Hawai'i (Woo, personal communication). Thus, methane reclamation efforts are concentrating on onsite use of methane. In 1984, the state estimated (again, perhaps over-optimistically) that refitting of existing sewage treatment plants to make use of the methane they generate could pay for itself via energy savings in as little as five years (State of Hawai'i, 1984, p. 32). The Kailua plant is indeed currently taking this into account in its expansion plans, with facility siting at Kane'ohe Marine Corps Air Station a likely scenario in order to assuage community complaints regarding smell and noise (*Honolulu Advertiser*, June 8, 1997, p. A29). In hopes that this scenario will play out, the county is taking a hard look at constructing a facility—with costs split between it and the federal government—to recycle sludge, methane and effluent, the latter for golf course irrigation (Woo, personal communication). Such programs should be supported by both the community and the state.

A benefit/cost analysis by the (then) Hawai'i Department of Planning and Economic Development (DPED) in 1984 concluded that the methane produced by the anaerobic digestion process could cover 75% to 100% of the overall power costs (anaerobic and aerobic) for all of Hawai'i's municipal wastewater treatment plants through generation of power, steam, and/or profits from offsite sales of methane (State of Hawai'i, 1984, p. 29, 37 and 50). Although perhaps overoptimistic in light of the 1990 study above, this power is equivalent to the percentage range of energy generated onsite by the Hyperion Sewage Treatment Plant, which services the greater Los Angeles area. Hyperion achieves this percentage by proceeding to dry and burn its digested solids (EPA, 1995b, p. 24 and 61).

To summarize this discussion, it appears that overall operating costs are lower for plants which primarily use anaerobic treatment, then use the methane to power equipment or generate heat onsite. Of the processes analyzed by the 1984 DPED report, the one with the lowest overall cost employed anaerobic treatment using a technology known as a biofilter, with sludge being treated first in an aerobic trickling filter and then in a separate flow-through anaerobic reactor (Table 20).

Cost Component	Activated Sludge (Aerobic)	Biofilter (Anaerobic)
Energy Required (kWh)	1,000	75
Sludge Produced (lb)	227	23
Conditioning Chemical (lb)	1	0
Nitrogen (lb)	23	2
Phosphorus (lb)	5	0
Cost[1]	139	12
Methane Production (ft^3)	0	11,429
Net Income (Cost)	($139)	$40

Table 20. Economics of treating municipal wastewater using activated sludge vs. biofilter treatment. Based on removing 2,200 lb COD from wastewater with 3.1 lb COD/ton. [1]Assumes $4.58/1,000ft^3 for natural gas, 8 cents/kWh for electric power, $80/million tons for disposal of sludge, and $250/million tons for phosphate and ammonia nutrients. From State of Hawai'i (1984), p. 46.

As noted in the Animal Manure section above, anaerobic digestion plants can also be used on large farms. A benefit/cost analysis of 61 such plants on French farms concluded that they paid for themselves in an average of 17 years, not including maintenance costs. This period is too long for most investors to consider, especially since it approaches the expected lifespan of some plants. Yet the French study also made the interesting discovery that the more money invested in the plant at the outset, the quicker the payoff. For example, plants that cost more than 400,000 francs (about $70,000) to build paid for themselves in an average of only 13 years, in part by having a higher percentage of the energy produced by the methane available for sale (70%) than did smaller plants (30%) (Heduit et al., 1986, p. 91). Unfortunately, as noted earlier, the benefits of such economies of scale probably exclude all but the largest livestock operations in the Hawaiian islands.

Large centralized plants which would accept biowaste from several farms and from sewage treatment plants, such as the currently-operating Unisyn plant (see Animal Waste Management section above) would probably be the best option for Hawai'i. Such a system, when fully integrated to make use of all outputs (energy, heat, fertilizer and irrigation) and fed by pipe from several nearby farms, has been calculated for Europe to require a total average investment of 8.5 million ECU (about $7.4 million), and be capable of paying for itself within five years (Naveau, 1986, p. 100). A similar study in Belgium required assessment of "fringe benefits" arising from pollution reduction to arrive at a payback period of four years (Nyns and Ferrero, 1986, p. 146-147). A comprehensive benefit/cost analysis of a DM 1.5 million ($2.5 million) sewage treatment plant in Germany which was upgrading its methane to pipeline quality found that the plant was turning a profit of about DM 236,000 ($393,000) per year, even calculating in both maintenance and 10-year amortization costs (Haydt and Schanz, 1986, p. 171-173).

Thus, it seems possible that an economic analysis of anaerobic sewage treatment systems in Hawai'i which accounted for overall energy efficiency, avoided greenhouse gas emissions, avoided fumes (if any), and other externalities would cast these systems in a fresh light. Regrettably, the Hawai'i-specific data remain too scanty to accomplish a comprehensive cost/benefit analysis. As a result, the projected trendlines in Figure 9 at the beginning of this document simply assume a conservative 35% reduction in statewide methane emissions if each county establishes one anaerobic WWTP in the next 20 years, serving its largest urban area. Further reductions—to about half the projected methane emissions if no mitigation was attempted—are considered possible if the state and counties enact the other sewage management options described below (Figure 9). The counties should not give up their attempts to initiate properly-designed anaerobic WWTPs, and should work with the public to increase acceptance of these somewhat maligned systems.

2. Directly Apply Dried Sewage Sludge as Fertilizer and Use Sewage Effluent for Nutrient-Rich Irrigation (moderate cost, moderate benefit)

Sewage sludge can be a cheap and effective fertilizer or soil conditioner when applied to pasture or farm land. Once pathogens and heavy metals have been reduced to background levels, it is legal to apply sewage sludge to edible crops in the U.S. (Statute 40 CFR 503). This is not currently being done in Hawai'i, however, due to a lack of cost-effectiveness and public support. A company by the name of Enviro attempted to market sewage sludge from its property in Campbell Industrial Park a few years ago, using alkali to raise the pH and kill pathogens, but the project was doomed by the combination of an inability to acquire permits and the opposition of neighboring businesses (Takazaki, personal communication). As noted elsewhere in this report, however, composting of sewage sludge is an established practice on Maui, and is being considered on O'ahu (Harder, personal communication).

Yet even without composting, digested sludge becomes easily transportable and marketable when dried, typically on a bed of sand. By the mid-1980s, O'ahu floral companies were already using up to 150 cubic yards of dried sludge annually as a potting mix (State of Hawai'i, 1984, p. 47). Even the National Research Council has recently declared that,

> *While no disposal or reuse option can guarantee complete safety, the use of these materials [biosolids and reclaimed water] in the production of crops for human consumption, when practiced in accordance with existing federal guidelines and regulations, presents negligible risk to the consumer, to crop production, and to the environment (quoted in WEF Highlights **33**(3), p. 1).*

Such application is not a panacea, however: It is estimated that all the sewage sludge produced in the U.S. could supply only 1-2% of the nation's annual fertilizer nitrogen need

(Laws, 1993, p. 144). Yet reduced fertilizer usage remains a key benefit that needs to be figured into the overall cost/benefit calculation for direct application of sewage sludge.

As an example to emulate, the city of Seattle has had a program in place since 1983 which applies all of its sewage sludge (about 18,150 tons of dry solids/year of anaerobically digested, primary and secondary-treated sludge) to land operations. Of this sludge, 65% is applied to forest lands, 25% is targeted for overall soil improvement, and 10% is composted for the horticultural market. Researchers associated with this project claim that commercially-acceptable trees can be harvested in 15% to 20% less time than with commercial urea fertilizers (Figure 19). Dewatered sludge cake with 18% to 25% dry solids is trucked as much as 60 miles to forest plantations, then rewatered to 10% to 13% dry solids to allow pump spraying. The cost of operation was $31.31 per wet ton in 1988 (Nichols, 1991, p. 158-162). At present, such application of sewage sludge would probably meet public opposition in Hawai'i, but done in the proper place with the proper safeguards, and with a comprehensive public education and community relations program (as is done in Seattle), it could provide a positive use of sewage sludge in Hawai'i which would significantly reduce methane emissions.

The primary drawback to land application of sewage sludge appears to be the accumulation of heavy metals in typical agricultural soils, and their uptake by crop roots (Laws, 1993, p. 145). However, the limited amount of industrial activity in Hawai'i should minimize this hazard. A second drawback is more serious from the greenhouse gas emissions standpoint: It is now well-established that forest and grassland soils can act as sinks for atmospheric methane, and that these sinks can effectively be turned off by nitrogen addition in the form of fertilizers and sewage sludge. Reduction in methane uptake capacity by soils tends to average about 87% (Paustian et al., 1995, p. 76-77). However, since the methane uptake capacity of Hawaiian soils is unknown, it is difficult to quantify the hazard. Economically, the primary negative factor is the cost of sludge transport and application, which would likely have to be borne by the state in order for the sludge to be cost-competitive with commercial fertilizer (Laws, 1993, p. 144). In spite of these drawbacks, nationwide between 15% and 20% of municipal sewage sludge is currently being applied to the land (Laws, 1993, p. 146).

Sewage sludge application to tree plantations has been studied on the mainland for some time. In Hawai'i, the two tree types which have received the most attention for plantation cultivation are varieties of eucalyptus and pine (see Land Use section above). The results of one mainland study on sludge application to stands of these and other tree types is shown in Table 21.

	Loblolly Pine	Virginia Pine	Sweet Gum	Green Ash	Yellow Poplar
Height Growth Increase Over Commercial Fertilizer	56%	67%	489%	xxx	xxx
Diameter Growth Increase Over Commerial Fertilizer	66%	101%	453%	xxx	xxx
Biomass Growth Increase Over Commercial Fertilizer	42%	xxx	123%	278%	661%

Table 21. Growth response of various tree species to sludge fertilization in the southeast United States. From Nichols, 1991, p. 158.

From this table, it appears that sewage sludge may in some cases perform significantly better than commercial fertilizer when applied to eucalyptus (gum) trees, but not when applied to pine varieties. Thus, any sewage sludge application to tree plantations in Hawai'i should concentrate on the former.

In addition to sludge, sewage effluent can also be used for land application, and virtually all of the studies conducted to date have concluded that this is a safe and practical way to dispose of sewage wastewater if reasonable precautions are exercised. The principal limiting factors appear to be the amount of land required and the accumulation of nitrate in groundwater supplies. Nitrate accumulation is of particular concern in Hawai'i for two reasons. First, experiments on the mainland have experienced sewage effluent percolating through the soil so quickly that crop roots were unable to filter out much nitrogen, to the point where additional fertilizer had to be added to make up the deficit (Laws, 1993, p. 138 and 141). Second, soils beneath former sugar and pineapple plantations in Hawai'i tend to have alarmingly high nitrate concentrations already. However, if land application is practiced in areas seaward of the limit of potable groundwater, such as is currently being planned near Barbers Point, O'ahu, the nitrate problem should be essentially eliminated. Other possible drawbacks, such as accumulation of pathogens, heavy metals and salts, have been found to be insignificant over the short-to-medium term in most cases, but over a period of decades the effects tend to become apparent in the form of declining crop yields (Laws, 1993, p. 139-140).

The EPA recommends land application of primary treated sewage if the crops are not intended for human consumption (e.g., for cattle fodder). Secondary treated sewage should be applied to crops destined for human consumption only if the crops are canned or similarly processed before sale (State of Hawai'i Administrative Rule Title 11, Chapter 62). These recommendations are not binding (Laws, 1993, p. 142), but Hawai'i law does require that even secondary treated sewage effluent cannot be applied to any vegetable crop. Treated effluent can, however, be used on sugarcane, pineapple and on crops not destined for human consumption, such as forage crops (Yee, personal communication). Effluent has also found increasing acceptance for nutrient-rich irrigation of golf courses and flower plantations (State of Hawai'i, 1984, p. 47). Currently, only about 5% (8 million gallons per day) of Hawai'i's wastewater is reused, mainly on golf courses. Yet it has been estimated that nearly 50% (75 million gallons per day) is emitted sufficiently near to irrigation areas to merit its reuse. This irrigation could provide water to some 15,000 acres, or around 100 golf courses (Ferguson et al., 1996, p. 3). However, distribution costs are not insignificant: on Maui, these costs range between $0.42 and $1.04 per 1,000 gallons (Ferguson et al., 1996, p. 4).

Side benefits of sludge and effluent reuse:

- Eliminates cost of incineration and (for irrigation) of dewatering.
- Reduces the need for energy to manufacture chemical fertilizers.
- Cheaper than commercial fertilizers (Department of Planning and Economic Development, 1984, p. 47).
- As with composting, diversion of sludge from landfills avoids costs for H_2S scrubbing at landfills which collect and burn their methane;
- In Seattle, application on forest land has actually led to an increase in floral and faunal health and fertility, with no buildup of contaminants in body tissues (Nichols, 1991, p. 201).

3. Compost Sewage Sludge for Use on Vegetables and Other Crops and Pastures (moderate cost, moderate benefit)

For a discussion of the possibilities of sewage sludge compost, see the section on fertilizers above. A comparison of the costs and benefits of composting vs. landspreading of sewage sludge from four projects in France was shown earlier in Table 16. Due to low prices for compost, all four projects in Table 16 were unprofitable. However, the project with the lowest capital and operating costs (a landspreading operation with capital costs of 1.2 million francs) was not the project with the lowest annual net cost. Instead, the least costly operation was a windrow composting plant which managed to procure a contract with a private company to purchase all of the plant's compost at a relatively good price (Table 16).

4. Inject CO_2 and Possibly Methane Into Sewage Effluent Being Sent Into Offshore Outfall Pipes (moderate to high cost, moderate to high benefit)

Sewage effluent contains some dissolved CO_2, but it has a capacity for significantly more. Injection of CO_2 into this effluent as it passes out into the outfall pipes of WWTPs would thus provide a way to sequester carbon below the sea surface for a certain period of time. Hawai'i's deepwater sewage outfalls tend to empty out near the thermocline (Miller, personal communication), and any CO_2 which mixes underneath the thermocline can be sequestered for significantly longer than that which remains in shallower water. Costs for such a process would be only moderate to high, consisting mainly of energy costs for aeration of the effluent with CO_2. Both the costs and the benefits should be studied in detail, since this process could sequester a fairly large volume of CO_2 on a constant basis. In particular, some method needs to be developed to determine the average residence time of this CO_2 in the water column at various outfalls under various conditions. This process could also form a sink for methane, but this should be approached cautiously since methane is an explosive gas which also could be toxic to aquatic life in sufficient concentrations. This process could not form a sink for N_2O, since one of the main goals of sewage treatment is to remove nitrogen from wastewater in the first place.

5. Use Sewage Effluent as Reinjection Fluid for Geothermal Wells in the Puna District of the Big Island (high cost, low benefit)

Geothermal energy currently provides about 35 MW of energy on the Big Island. This project has made some use of equipment which reinjects water (cooled from geothermal steam) back into the underground formations to allow the water to reheat. The system has had some problems, however, due to corrosive acids and other materials retained in the reinjected water. In California, the Geysers geothermal site, which generates over 1,000 MW of energy, has been losing about 6% of its power production annually since the mid-1980s due to declining steam concentrations in the subsurface. A project to pipe sewage effluent 26 miles to the site was scheduled to go on-line in late 1996 or early 1997 (EPA, 1995b, p. 55-57).

Sewage may have benefits over geothermal wastewater for reinjection. Such a project would have high costs, however, in particular the cost of pipeline construction and maintenance. In addition, the geothermal plants on the Big Island are neither large nor experiencing significant power decreases due to diminishing steam resources. Thus, this possibility should not be considered a viable solution in the near term.

G. Intersectorial Measures

While some of the measures discussed above could fit under more than one sector heading (in particular composting), some additional options apply to most or all of these sectors. These measures require concerted action by the state and county governments. The programs listed below would have several positive aspects in addition to their direct benefits, including: (a) providing additional support for the more sector-specific measures discussed earlier; (b) placing the state and counties in a better position to request or require similar efforts from the private sector; (c) providing expertise to private operations and a proving ground for new technology; and (d) educating public workers in ways that may impact their own practices as consumers (State of Hawai'i, 1991, p. G-2).

1. **Provide Certain Areas with Titles Designating Their Sensitivity to Agents which Contribute to Greenhouse Gas Emissions (low cost, moderate benefit).**

Such designations could help raise public awareness and attract federal funds for their study and protection, without the need for increased regulatory measures.

a. *Designate certain bays, such as Kane'ohe Bay, Mamala Bay and Hilo Bay as Nutrient-Sensitive Areas, in the same manner as Chesapeake Bay (IPCC, 1991, p. 114).*

   This designation could imitate the model of the recently-expanded Hawaiian Islands Humpback Whale Sanctuary, which provides no additional regulation yet attracts both visitors and federal funding while raising public awareness on the condition of humpback whales.

b. *Designate certain agricultural areas and/or watersheds as soil conservation areas, where the relevant measures discussed in this document are particularly stressed.*

2. **Establish a Statewide Greenhouse Gas Reduction Program with Specific Goals and a Full-Time Staff Tasked with Implementation, Monitoring and Public Education (moderate cost, moderate benefit).**

This option could use the Action Plan detailed at the beginning of this report as a blueprint.

3. **Create a Database Regarding Activities which Affect Greenhouse Gas Emissions (moderate cost, moderate benefit).**

This database could also be used to promote and market products of recycling, composting and other waste management programs by linking different parts of these industries together. As such, this database could be managed by either DBEDT, DOH or both (State of Hawai'i, 1991, p. ES-5).

V. CONCLUSION

This report presents a comprehensive list of measures aimed at mitigating non-energy sources of greenhouse gas emissions in the state of Hawai'i. Certainly not all are implementable in the near future, and some may never be feasible. The list has been prioritized in an attempt to account for both the cost-effectiveness of each measure and the uncertainty of its technological, legal and/or social feasibility. While some of these suggestions must be tabled at present, this document can help guide research into those measures that may be more promising in the long term.

The geographic setting of Hawai'i provides a unique opportunity for this state to serve as a microcosm for testing and implementation of strategies to reduce greenhouse gas emissions. Methodologies undertaken here can contribute to global models for proactive programs to reduce sources of greenhouse gas emissions thus helping to reduce the unforeseen impacts of global climate change.

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Appendix A

Contact List for Phase II

Appendix A:

Contact List for Phase II

Name and Organization	Source Categories
City and County of Honolulu	
Department of Refuse Collection and Disposal *Ms. Wilma Namunart* Chief Engineer (808) 527-5378	landfills, recycling, composting
Department of Wastewater Management *Mr. Doug Woo* Public Information Officer (808) 527-6669	wastewater
County of Hawaii	
Department of Solid Waste *Mr. Larry Capelis* Solid Waste Engineer (808) 961-8339	landfills, recycling, composting
County of Kauai	
Department of Public Works *Mr. Troy Tanegawa* Solid Waste Engineer Solid Waste Division, Lihue (808) 241-6880	landfills, recycling, composting
County of Maui	
Department of Public Works and Waste Management *Ms. Elaine Baker* Civil Engineer Division of Solid Waste, Kahului (808) 243-7874	landfills, recycling
Department of Public Works and Waste Management *Ms. Irene Cordell* Recycling Coordinator Division of Solid Waste, Kahului (808) 243-7870	recycling
Department of Public Works and Waste Management *Mr. Andy Hirose* Solid Waste Engineer Division of Solid Waste, Kahului (808) 243-7875	landfills

Hapuna Golf Course *Mr. Milton Nakagawa* Superintendent-in-Charge Hapuna Resort, Hawaii Island (808) 880-3000	fertilizers
Hawaii Agricultural Statistics Service *Ms. Stephanie Whalen* Information Officer Honolulu (808) 486-5310	agricultural trends biomass-to-energy
Hawaiian Earth Products *Various personnel* Campbell Industrial Park (808) 682-5895	composting
Honolulu Resource Recovery Venture (H-POWER) *Mr. Colin Jones* Information Coordinator Campbell Industrial Park (808) 692-1359	waste-to-energy
IMC Vigoro Professional Products, Inc. *Mr. David Klawitter* Sales Representative Honolulu (808) 841-3305	fertilizers
King Diesel, Inc. *Mr. Larry King* Co-owner Kahului, Maui (808) 871-6624	energy from biomass
Safeway, Inc. *Produce Department Employee* Manoa Marketplace , Honolulu (808) 988-2058	produce costs
State of Hawaii Department of Agriculture *Dr. Jason Moniz* Program Manager Livestock Disease Control Branch Animal Industry Division (808) 483-7118	animal feed manure management livestock benefit/cost

State of Hawaii (continued)

Department of Agriculture *Dr. Larry Rauson* Livestock Biologist Livestock Disease Control Branch Animal Industry Division (808) 483-7119	animal feed
Department of Agriculture *Mr. Earl Yamamoto* Planner Planning and Development Office (808) 973-9466	wastewater manure
Department of Business, Economic Dev't & Tourism *Mr. Robert Wood* Director Clean Hawaii Center Energy, Resources and Technology Division (808) 587-3802	recycling
Department of Health *Mr. John Harder* Coordinator Office of Solid Waste Management Solid and Hazardous Waste Management Branch (808) 586-4240	landfills composting wastewater biomass-to-energy
Department of Health *Ms. Carolyn McCabe* State Recycling Coordinator Office of Solid Waste Management Solid and Hazardous Waste Management Branch (808) 586-4240	recycling composting wastewater
Department of Health *Ms. Gail Takazaki* Environmental Engineer Wastewater Branch (808) 586-4290	wastewater composting
Department of Health *Mr. Harold Yee* Supervisor Planning and Design Section Wastewater Branch (808) 586-4294	wastewater composting manure

State of Hawaii (continued)	
Department of Land and Natural Resources *Mr. Nelson Ayers* Forester Administrative Branch Forestry and Wildlife Division (808) 587-0166	afforestation biomass-to-energy
Department of Land and Natural Resources *Mr. Carl Masaki* Manager Forestry Program Forestry and Wildlife Division (808) 587-0166	afforestation
Unisyn Biowaste Technology, Inc. *Mr. Matt Lyum* Operations Manager, Waimanalo (808) 259-8877	waste-to-energy wastewater animal feed
University of Hawaii	
Department of Agronomy and Soil Sciences *Dr. Goro Uehara* Soil Scientist (808) 956-6593	fertilizers
Department of Animal Science *Dr. Chin Lee* Associate Dairy Specialist (808) 956-4882	animal feed manure composting
Department of Animal Science *Dr. Halina Zaleski* Assistant Extension Specialist (808) 956-7594	animal feed manure livestock benefit/cost
Department of Biosystems Engineering *Dr. Daniel Paquin* Mechanical Engineer (808) 956-7259	manure
Department of Geography *Mr. Michael Parke* Lecturer (808) 956-7428	landfills, recycling

University of Hawaii (continued)

Environmental Center *Dr. John Harrison* Environmental Coordinator (808) 956-3968	recycling
Environmental Center *Dr. Jackie Miller* Associate Environmental Coordinator (808) 956-7362	wastewater
Hawaii Natural Energy Institute *Dr. Charles Kinoshita* Research Engineer (808) 956-2343	biomass-to-energy
Hawaii Natural Energy Institute *Dr. Steve Masutani* Associate Researcher (808) 956-7388	biomass-to-energy
Office of Administration *Mr. Allan Ah San* Associate Vice President for Administration (808) 956-7935	recycling

Appendix B

Spreadsheet Calculations for Baseline Landfill Emissions Trend

Growth/yr	Year	State de Facto Population (July 1)	O'ahu De Facto Population (July 1)	De Facto Population of Neighbor Islands	Calculated WIP *on Neighbor Is.* (tons)	WIP *on O'ahu* if No Burning (tons)*	Amount Used for H-POWER (tons)	Amount to Waipahu Incinerator (tons)'	Oahu Waste in Place (WIP) (tons)F	Statewide WIP in Small Landfills (tons)	Statewide WIP in Large Landfills (tons)	Methane from Small Landfills (M_S) (T/yr)	Methane from Large Landfills (M_L) (T/yr)	Methane from All Landfills (tons/yr)	Methane Recovery (tons/yr)**	Methane Flaring (tons/yr)***	Adjusted for CH_4 Flaring & Recovery (tons/yr)	Adjusted for CH_4 Oxidation (tons/yr)
	1980	1,055,400	823,400	232,000	3,582,466	12,714,665	0	156,429	12,558,236	6,698,391	9,442,311	18,052	30,991	49,043	0	0	49,043	44,139
	1981*	1,062,600	824,700	237,900	3,673,571	13,414,665	0	156,429	13,101,808	6,961,782	9,813,597	18,762	31,448	50,210	0	0	50,210	45,189
	1982*	1,084,600	837,600	247,000	3,814,091	14,124,665	0	156,429	13,655,379	7,249,830	10,219,640	19,538	31,948	51,487	0	0	51,487	46,338
	1983*	1,109,200	846,300	262,900	4,059,613	14,844,665	0	156,429	14,218,951	7,585,604	10,692,960	20,443	32,532	52,975	0	0	52,975	47,677
	1984*	1,130,500	852,300	278,200	4,295,870	15,574,665	0	156,429	14,792,522	7,921,683	11,166,710	21,349	33,115	54,464	0	0	54,464	49,018
	1985	1,137,800	854,800	283,000	4,369,990	16,324,665	0	156,429	15,386,094	8,198,775	11,557,309	22,096	33,596	55,692	0	0	55,692	50,123
	1986	1,167,500	871,000	296,500	4,578,453	17,074,665	0	156,429	15,979,665	8,531,619	12,026,499	22,993	34,174	57,167	0	0	57,167	51,450
	1987	1,186,500	881,000	305,500	4,717,428	17,849,665	0	156,429	16,598,236	8,846,001	12,469,664	23,840	34,720	58,560	0	499	58,061	52,255
	1988	1,200,400	888,200	312,200	4,820,887	18,627,665	0	156,429	17,219,808	9,146,888	12,893,806	24,651	35,243	59,894	0	1,497	58,397	52,557
	1989	1,245,600	905,900	339,700	5,245,533	19,552,665	0	156,429	17,988,379	9,642,073	13,591,838	25,985	36,103	62,088	0	1,497	60,592	54,532
	1990	1,257,000	912,100	344,900	5,325,829	20,507,665	495,000	78,214	18,865,165	10,039,263	14,151,732	27,056	36,793	63,849	2,228	1,497	60,124	54,111
	1991	1,274,800	916,500	358,300	5,532,748	21,557,665	583,000	78,214	19,253,951	10,286,480	14,500,218	27,722	37,222	64,944	4,973	1,497	58,474	52,627
	1992	1,269,400	911,700	357,700	5,523,483	22,584,543	614,000	78,214	19,588,614	10,421,520	14,690,577	28,086	37,457	65,543	4,246	1,497	59,800	53,820
	1993	1,265,100	909,100	356,000	5,497,232	23,608,034	591,000	78,214	19,942,891	10,557,651	14,882,472	28,453	37,693	66,146	2,828	1,497	61,821	55,639
Growth/yr	1994	1,287,600	920,500	367,100	5,668,634	24,610,174	589,000	32,143	20,323,888	10,786,897	15,205,626	29,071	38,091	67,162	4,142	1,497	61,524	55,371
0.48%	1995****	1,287,100	915,400	371,700	5,739,666	25,583,428	633,000	0	20,664,142	10,957,580	15,446,228	29,531	38,388	67,918	4,125	1,497	62,296	56,067
	1996	1,304,218	924,160	380,058	5,868,734	26,555,598	630,000	0	21,006,313	11,153,144	15,721,902	30,058	38,727	68,785	9,476	1,497	57,812	52,031
	1997	1,321,565	932,920	388,645	6,001,318	27,564,711	650,000	0	21,365,425	11,357,198	16,009,545	30,608	39,082	69,689	9,476	1,497	58,716	52,845
	1998	1,339,776	941,680	398,096	6,147,259	28,612,170	650,000	0	21,762,884	11,582,710	16,327,434	31,215	39,473	70,689	9,476	1,497	59,716	53,744
	1999	1,357,595	950,440	407,155	6,287,146	29,699,432	650,000	0	22,200,147	11,822,226	16,665,066	31,861	39,889	71,750	9,476	1,497	60,777	54,699
1.33%	2000	1,372,800	959,200	413,600	6,386,671	30,828,011	650,000	0	22,678,725	12,062,140	17,003,257	32,507	40,306	72,813	16,357	3,218	53,239	47,915
	2001	1,390,784	968,760	422,024	6,516,747	31,999,475	650,000	0	23,200,190	12,332,529	17,384,408	33,236	40,775	74,012	16,357	3,218	54,437	48,993
	2002	1,409,003	978,320	430,683	6,650,461	33,215,455	650,000	0	23,766,170	12,622,902	17,793,729	34,019	41,280	75,298	16,357	3,218	55,724	50,151
	2003	1,427,461	987,880	439,581	6,787,860	34,477,643	650,000	0	24,378,357	12,933,980	18,232,237	34,857	41,820	76,677	16,357	3,218	57,102	51,392
	2004	1,446,161	997,440	448,721	6,928,992	35,787,793	650,000	0	25,038,507	13,266,512	18,700,987	35,753	42,397	78,151	16,357	3,218	58,576	52,718
1.31%	2005	1,463,000	1,007,000	456,000	7,041,398	37,147,729	650,000	0	25,748,444	13,607,784	19,182,057	36,673	42,990	79,663	20,939	3,218	55,507	49,956
	2006	1,480,117	1,015,380	464,737	7,176,313	38,559,343	650,000	0	26,510,057	13,979,844	19,706,527	37,676	43,636	81,312	20,939	3,218	57,156	51,440
	2007	1,497,434	1,023,760	473,674	7,314,321	40,024,598	650,000	0	27,325,312	14,375,448	20,264,186	38,742	44,323	83,065	20,939	3,218	58,909	53,018
	2008	1,514,954	1,032,140	482,814	7,455,458	41,545,533	650,000	0	28,196,247	14,795,457	20,856,247	39,874	45,053	84,926	20,939	3,218	60,770	54,693
	2009	1,532,679	1,040,520	492,159	7,599,760	43,124,263	650,000	0	29,124,977	15,240,766	21,483,971	41,074	45,826	86,900	20,939	3,218	62,744	56,469
1.17%	2010	1,548,600	1,048,900	499,700	7,716,199	44,762,985	650,000	0	30,113,699	15,699,408	22,130,490	42,310	46,623	88,932	24,847	3,218	60,868	54,781
	2011	1,566,719	1,057,180	509,539	7,868,123	46,463,978	650,000	0	31,164,693	16,198,619	22,834,197	43,655	47,490	91,145	24,847	3,218	63,081	56,773
	2012	1,585,049	1,065,460	519,589	8,023,321	48,229,610	650,000	0	32,280,324	16,726,013	23,577,632	45,077	48,405	93,482	24,847	3,218	65,418	58,876
	2013	1,603,594	1,073,740	529,854	8,181,831	50,062,335	650,000	0	33,463,049	17,282,625	24,362,255	46,577	49,372	95,949	24,847	3,218	67,885	61,096
	2014	1,622,356	1,082,020	540,336	8,343,691	51,964,703	650,000	0	34,715,418	17,869,530	25,189,579	48,158	50,391	98,550	24,847	3,218	70,486	63,437
1.09%	2015	1,633,300	1,090,300	543,000	8,384,823	53,939,362	650,000	0	36,040,076	18,436,333	25,988,566	49,686	51,376	101,062	33,326	6,971	60,765	54,688
	2016	1,651,103	1,098,360	552,743	8,535,270	55,989,058	650,000	0	37,439,772	19,079,643	26,895,400	51,420	52,493	103,913	33,326	6,971	63,616	57,254
	2017	1,669,100	1,106,420	562,680	8,688,714	58,116,642	650,000	0	38,917,356	19,756,519	27,849,551	53,244	53,668	106,912	33,326	6,971	66,615	59,954
	2018	1,687,293	1,114,480	572,813	8,845,188	60,325,075	650,000	0	40,475,789	20,468,205	28,852,771	55,162	54,904	110,066	33,326	6,971	69,769	62,793
	2019	1,705,685	1,122,540	583,145	9,004,723	62,617,427	650,000	0	42,118,142	21,215,989	29,906,876	57,177	56,203	113,380	33,326	6,971	73,083	65,775
1.06%	2020	1,720,200	1,130,600	589,600	9,104,404	64,996,890	650,000	0	43,847,604	21,975,083	30,976,925	59,223	57,521	116,744	33,326	6,971	76,447	68,803

Table B1: Landfill methane emissions for Hawai'i by individual landfills, 1980-2020: Accounting for burning of refuse and methane, and including 1985-1995 WIP records from O'ahu.

**WIP values for O'ahu are interpolated between 1980 (as calculated via EPA methods) and 1985 (when county records begin). Excludes construction/demolition waste & recycled materials.*

'Annual incinerator tonnage calculated assuming 600 T/day, 5 days/week until 1990, then 300 T/day to mid-1994.

***Methane recovered at Kapa'a Landfill, Waimanalo, O'ahu, starting in 1990. From 2000, assume that every 5 years one additional large LF recovers methane, at 80% efficiency.*

****Methane flared at Olowalu and Makani Landfills on Maui, and Halehaka Landfill on Kaua'i. From 2000, assume that every 5 years one additional landfill flares its methane, at 80% efficiency.*

*****Projected population data, courtesy of Research and Economic Analysis Division, Hawai'i State Department of Business, Economic Development and Tourism.*

FCalculated by subtracting the sum of all tonnages burned in previous years (i.e., tonnages which did not go into landfills).

Growth/yr	Landfill	Hilo Landfill	New Hilo Landfill	W. Hawai'i Landfill	Central Maui LF	New Ctrl Maui LF	Hana Landfill	Olowalu & Makani LFs	Lana'i Landfill	New Lana'i Landfill	Kalama'ula Landfill	New Molo-ka'i LF	Kapa'a Central LF	Kapa'a Site 2	Kapa'a Site 3
	per yr, '95	*143.3*	*0.0*	*129.0*	*350.1*	*0.0*	*2.9*	*0.0*	*3.9*	*0.0*	*0.0*	*8.3*	*0.0*	*0.0*	*0.0*
0.60%	1995	1,734	0	1,473	5,648	0	45	998	79	0	449	29	5,727	0	3,855
	1996	1,873	0	1,600	5,992	0	48	998	83	0	449	37	5,727	0	3,855
	1997	2,011	0	1,727	6,336	0	51	998	87	0	449	46	5,727	0	3,855
	1998	2,151	0	1,858	6,689	0	54	998	91	0	449	55	5,727	0	3,855
	1999	2,151	141	1,991	6,689	360	56	998	95	0	449	64	5,727	0	3,855
1.42%	2000	2,151	285	2,128	6,689	728	59	998	99	0	449	74	5,727	0	3,855
	2001	2,151	430	2,269	6,689	1,104	63	998	104	0	449	84	5,727	0	3,855
	2002	2,151	578	2,414	6,689	1,489	66	998	108	0	449	94	5,727	0	3,855
	2003	2,151	728	2,564	6,689	1,883	69	998	113	0	449	104	5,727	0	3,855
	2004	2,151	880	2,719	6,689	2,286	72	998	117	0	449	114	5,727	0	3,855
1.65%	2005	2,151	1,035	2,878	6,689	2,698	76	998	122	0	449	125	5,727	0	3,855
	2006	2,151	1,192	3,043	6,689	3,118	79	998	127	0	449	136	5,727	0	3,855
	2007	2,151	1,352	3,213	6,689	3,547	83	998	132	0	449	147	5,727	0	3,855
	2008	2,151	1,514	3,389	6,689	3,984	86	998	132	5	449	158	5,727	0	3,855
	2009	2,151	1,680	3,570	6,689	4,430	90	998	132	10	449	170	5,727	0	3,855
4.60%	2010	2,151	1,847	3,758	6,689	4,885	94	998	132	15	449	181	5,727	0	3,855
	2011	2,151	2,018	3,951	6,689	5,347	97	998	132	21	449	193	5,727	0	3,855
	2012	2,151	2,191	4,149	6,689	5,816	101	998	132	26	449	205	5,727	0	3,855
	2013	2,151	2,366	4,354	6,689	6,293	105	998	132	32	449	218	5,727	0	3,855
	2014	2,151	2,544	4,565	6,689	6,777	109	998	132	37	449	230	5,727	0	3,855
2.10%	2015	2,151	2,725	4,782	6,689	7,268	113	998	132	43	449	243	5,727	0	3,855
	2016	2,151	2,908	5,005	6,689	7,759	117	998	132	49	449	256	5,727	0	3,855
	2017	2,151	3,094	5,235	6,689	8,258	121	998	132	55	449	269	5,727	0	3,855
	2018	2,151	3,283	5,472	6,689	8,764	125	0	132	61	449	282	5,727	0	3,855
	2019	2,151	3,475	5,716	6,689	9,278	130	0	132	67	449	296	5,727	0	3,855
1.70%	2020	2,151	3,669	5,967	6,689	9,799	134	0	132	73	449	309	0	0	3,855

Table B2: Hawai'i estimated methane emissions by landfill, 1995-2020, if all parts of any landfill emit methane at a constant rate for 30 years, and no flaring of new landfills. Continued on following pages.

Old Kapa'a Landfills	Kapa'a LF (Constr'n)	Kawailoa Landfill	Wai'anae Landfill	Kalaheo Landfill	Waimanalo Landfill	New Wai-manalo LF	Nanakuli Landfill	New Nana-kuli Landfill	Pu'u Palailai LF	Kekaha Phase I LF	Kekaha Phase II LF	Kekaha Phase III LF	Halehaka LF	Total	
0.0	*0.0*	*0.0*	*0.0*	*0.0*	*687.2*	*0.0*	*35.3*	*0.0*	*0.0*	*0.0*	*141.6*	*0.0*	*0.0*	***1,501.7***	
798	333	2,421	4,692	4,598	3,855	0	458	0	6,158	1,050	683	0	499	**45,582**	1995
798	333	2,421	4,692	4,598	4,522	0	494	0	6,158	1,050	822	0	499	**47,049**	1996
798	333	2,421	4,692	4,598	5,183	0	530	0	6,158	1,050	962	0	499	**48,512**	1997
798	333	2,421	4,692	4,598	5,852	0	566	0	6,158	1,050	962	143	499	**49,998**	1998
798	333	2,421	4,692	4,598	6,527	0	603	0	6,158	1,050	962	289	499	**51,508**	1999
798	333	2,421	4,692	4,598	7,210	0	641	0	6,158	1,050	962	439	499	**53,042**	2000
798	333	2,421	4,692	4,598	7,901	0	678	0	6,158	1,050	962	593	499	**54,605**	2001
798	333	2,421	4,692	4,598	8,601	0	717	0	6,158	1,050	962	752	499	**56,197**	2002
798	333	2,421	4,692	4,598	8,601	708	755	0	6,158	1,050	962	915	499	**57,819**	2003
798	333	2,421	4,692	4,598	8,601	1,321	794	0	6,158	1,050	962	1,083	499	**59,368**	2004
798	333	2,421	4,692	4,598	8,601	1,942	834	0	6,158	1,050	962	1,257	499	**60,947**	2005
798	333	2,421	4,692	4,598	8,601	2,569	874	0	6,158	1,050	962	1,435	499	**62,554**	2006
798	333	2,421	4,692	4,598	8,601	3,202	914	0	6,158	1,050	962	1,618	499	**64,189**	2007
798	333	2,421	4,692	4,598	8,601	3,842	643	41	6,158	1,050	962	1,806	499	**65,581**	2008
798	333	2,421	4,692	4,598	8,601	4,487	643	82	6,158	1,050	962	1,999	499	**67,273**	2009
798	333	2,421	4,692	4,598	8,601	5,139	643	124	6,158	1,050	962	2,197	499	**68,996**	2010
798	333	2,421	4,692	4,598	8,601	5,797	643	165	6,158	1,050	962	2,399	499	**70,744**	2011
798	333	2,421	4,692	4,598	8,601	6,459	643	208	6,158	1,050	962	2,605	499	**72,517**	2012
798	333	2,421	4,692	4,598	8,601	7,127	643	250	6,158	1,050	962	2,816	499	**74,316**	2013
798	333	2,421	4,692	4,598	8,601	7,800	643	293	6,158	1,050	962	3,030	499	**76,141**	2014
798	333	2,421	4,692	4,598	8,601	8,479	643	337	6,158	1,050	962	3,249	499	**77,993**	2015
798	333	2,421	4,692	4,598	8,601	9,162	643	380	6,158	1,050	962	3,473	499	**79,865**	2016
0	333	2,421	4,692	4,598	8,601	9,851	643	424	6,158	1,050	962	3,700	499	**80,965**	2017
0	333	2,421	4,692	4,598	8,601	10,545	643	468	6,158	1,050	962	3,933	499	**81,892**	2018
0	333	2,421	4,692	4,598	8,601	11,243	643	513	0	1,050	962	4,170	499	**77,688**	2019
0	333	2,421	4,692	4,598	8,601	11,947	643	558	0	1,050	962	4,412	499	**73,943**	2020

Table B2 (continued): Hawai'i estimated methane emissions by landfill, 1995-2020, if all parts of any landfill emit methane at a constant rate for 30 years, and no flaring of new landfills. Continued on following page.

Avoided Emissions, Summed

	H-POWER	Recycling	Total
1995	9,449	6,670	16,119
1996	11,104	7,791	18,896
1997	12,748	8,999	25,401
1998	14,392	10,211	24,604
1999	16,036	11,429	27,466
2000	17,680	12,653	30,333
2001	19,324	13,882	33,206
2002	20,968	15,116	36,084
2003	22,612	16,356	38,968
2004	24,256	17,601	41,857
2005	25,900	18,852	44,752
2006	27,544	20,107	47,651
2007	29,188	21,369	50,557
2008	30,832	22,635	53,467
2009	32,476	23,907	56,383
2010	34,120	25,185	59,305
2011	35,764	26,468	62,231
2012	37,408	27,756	65,163
2013	39,052	29,049	68,101
2014	40,696	30,348	71,044
2015	42,340	31,653	73,992
2016	43,983	32,963	76,946
2017	45,627	34,278	79,905
2018	47,271	35,598	82,870
2019	48,915	36,924	85,840
2020	50,559	38,256	88,815

De Facto Population Projections

County	O'ahu	Hawai'i	Kaua'i	Maui	State
1995	921,700	150,000	69,400	153,600	1,294,700
2000	973,300	163,900	77,900	171,600	1,386,400
2005	1,033,200	184,600	90,600	192,400	1,500,600
2010	1,085,500	208,600	103,600	212,700	1,610,100
2015	1,129,800	233,300	114,700	229,800	1,707,600
2020	1,172,200	260,700	126,800	247,700	1,807,100

State and Counties Growth per Year

County	O'ahu	Hawai'i	Kaua'i	Maui	State
1996-2000	1.09%	1.77%	2.31%	2.21%	1.37%
2001-2005	1.19%	2.38%	3.01%	2.29%	1.58%
2006-2010	0.99%	2.44%	2.68%	2.00%	1.41%
2011-2015	0.80%	2.24%	2.03%	1.55%	1.18%
2016-2020	0.74%	2.22%	2.00%	1.50%	1.13%

Big Island Districts Growth per Year

District	Kona	Hilo	Total BI
1996-2000	2.36%	1.18%	1.77%
2001-2005	3.17%	1.58%	2.38%
2006-2010	3.26%	1.63%	2.44%
2011-2015	2.98%	1.49%	2.24%
2016-2020	2.96%	1.48%	2.22%

Average Landfill Composition in U.S.

Component	Percentage
Food Wastes	12.1
Garden Wastes	16.5
Paper	43.6
Plastic/Rubber	2.3
Textiles	1.5
Wood	1.7
Metal	8.2
Glass/Ceramic	7.5
Ash/Dirt/Rock	4.4
Miscellaneous	1.4
Total*	99.1

*Does not equal 100% due to rounding.
From Emcon Associates (1980).

Table B2 (continued): Hawai'i estimated avoided methane emissions, 1995-2020, and annual projected population growth per county. Population figures from State of Hawai'i, 1997a.

Landfill	Hilo Landfill	New Hilo Landfill	W. Hawai'i Landfill	Central Maui LF	New Cent'l Maui LF	Hana Landfill	Olowalu & Makani LFs	Lana'i Landfill	New Lana'i Landfill	Kalama'ula Landfill	New Moloka'i Landfill	Kapa'a Central LF	Kapa'a Site 2	Kapa'a Site 3	Old Kapa'a Landfills
per yr, '95	*143.3*	*0.0*	*129.0*	*350.1*	*0.0*	*2.9*	*0.0*	*3.9*	*0.0*	*8.3*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
1995	1,734	0	1,473	5,648	0	45	998	79	0	449	29	5,727	0	3,855	798
1996	1,873	0	1,600	5,992	0	48	998	83	0	457	37	5,727	0	3,855	798
1997	2,011	0	1,727	6,336	0	51	998	87	0	465	46	5,727	0	3,855	798
1998	2,151	0	1,858	6,689	0	54	998	91	0	474	55	5,727	0	3,855	798
1999	2,151	141	1,991	6,689	360	56	998	94	0	482	64	5,727	0	3,855	798
2000	2,151	285	2,128	6,689	728	59	998	99	0	491	74	5,727	0	3,855	798
2001	2,151	430	2,268	6,689	1,104	63	998	103	0	500	84	5,727	0	3,855	798
2002	2,151	578	2,414	6,689	372	66	998	107	0	509	94	5,727	0	3,855	798
2003	2,151	728	2,564	6,689	381	69	998	111	0	518	104	5,727	0	3,855	798
2004	2,151	880	2,719	6,689	390	72	998	116	0	528	114	5,727	0	3,855	798
2005	2,151	1,035	2,878	6,689	398	76	998	120	0	538	125	5,727	0	3,855	798
2006	2,151	298	3,043	6,689	408	79	998	125	0	548	136	5,727	0	3,855	798
2007	2,151	302	3,213	6,689	417	83	998	130	0	558	147	5,727	0	3,855	798
2008	2,151	307	3,389	6,689	426	86	998	130	5	568	158	5,727	0	3,855	798
2009	2,151	312	3,570	6,689	436	90	998	130	10	579	170	5,727	0	3,855	798
2010	2,151	316	3,758	6,689	446	94	998	130	15	589	181	5,727	0	3,855	798
2011	2,151	321	3,951	6,689	456	97	998	130	20	600	193	5,727	0	3,855	798
2012	2,151	326	4,150	6,689	466	101	998	130	25	611	205	5,727	0	3,855	798
2013	2,151	331	4,354	6,689	476	105	998	130	30	623	218	5,727	0	3,855	798
2014	2,151	336	4,565	6,689	487	109	998	130	36	634	230	5,727	0	3,855	798
2015	2,151	341	4,782	6,689	497	113	998	130	41	646	243	5,727	0	3,855	798
2016	2,151	346	5,006	6,689	508	117	998	130	47	658	256	5,727	0	3,855	798
2017	2,151	351	5,236	6,689	519	121	998	130	52	670	269	5,727	0	3,855	798
2018	2,151	356	5,473	6,689	530	125	998	130	58	682	282	5,727	0	3,855	798
2019	2,151	361	5,717	6,689	542	130	998	130	64	694	296	0	0	3,855	798
2020	2,151	367	5,968	6,689	553	134	998	130	70	707	309	0	0	3,855	798

Table B3. Hawai'i Estimated Methane Emissions by Landfill (1995-2020), if all parts of any landfill emit methane at a constant rate for 30 years, and new landfills are flared after they begin producing >1,000 tons CH_4/yr. Continued on following page.

				CH_4 Burned after 2005									
Kapa'a LF (Construct'n)	Kawailoa Landfill	Wai'anae Landfill	Kalaheo Landfill	Waimanalo Landfill	New Waimanalo Landfill	Nanakuli Landfill	New Nanakuli Landfill	Pu'u Palailai LF	Kekaha Phase I LF	Kekaha Phase II LF	Kekaha Phase III LF	Halehaka Landfill	**Total**
0.0	*0.0*	*0.0*	*0.0*	*687.2*	*0.0*	*35.3*	*0.0*	*0.0*	*0.0*	*141.6*	*0.0*	*0.0*	***1501.7***
333	2,421	4,692	4,598	3,855	0	458	0	6,158	1,050	683	0	499	**45,582**
333	2,421	4,692	4,598	4,522	0	494	0	6,158	1,050	822	0	499	**47,057**
333	2,421	4,692	4,598	5,183	0	530	0	6,158	1,050	962	0	499	**48,528**
333	2,421	4,692	4,598	5,852	0	566	0	6,158	1,050	1,105	0	499	**50,022**
333	2,421	4,692	4,598	6,527	0	603	0	6,158	1,050	1,251	0	499	**51,540**
333	2,421	4,692	4,598	7,210	0	641	0	6,158	1,050	1,401	0	499	**53,083**
333	2,421	4,692	4,598	7,902	0	678	0	6,158	1,050	1,555	0	499	**54,655**
333	2,421	4,692	4,598	8,601	0	717	0	6,158	1,050	1,713	0	499	**55,139**
333	2,421	4,692	4,598	8,601	708	755	0	6,158	1,050	1,877	0	499	**56,384**
333	2,421	4,692	4,598	8,601	1,424	794	0	6,158	1,050	1,877	168	499	**57,651**
333	2,421	4,692	4,598	8,601	537	834	0	6,158	1,050	1,877	342	499	**57,329**
333	2,421	4,692	4,598	4,300	542	874	0	6,158	1,050	1,877	520	499	**52,719**
333	2,421	4,692	4,598	2,580	548	914	0	6,158	1,050	1,877	703	499	**51,441**
333	2,421	4,692	4,598	2,150	553	955	0	6,158	1,050	1,877	891	499	**51,464**
333	2,421	4,692	4,598	2,150	559	996	0	6,158	1,050	1,877	1,084	499	**51,930**
333	2,421	4,692	4,598	2,150	564	1,038	0	6,158	1,050	1,877	320	499	**51,446**
333	2,421	4,692	4,598	2,150	570	259	41	6,158	1,050	1,877	327	499	**50,960**
333	2,421	4,692	4,598	2,150	575	259	83	6,158	1,050	1,877	333	499	**51,260**
333	2,421	4,692	4,598	2,150	581	259	125	6,158	1,050	1,877	340	499	**51,568**
333	2,421	4,692	4,598	2,150	587	259	168	6,158	1,050	1,877	347	499	**51,882**
333	2,421	4,692	4,598	2,150	593	259	210	6,158	1,050	1,877	353	499	**52,204**
333	2,421	4,692	4,598	2,150	598	259	254	6,158	1,050	1,877	361	499	**52,534**
0	2,421	4,692	4,598	2,150	604	259	297	6,158	1,050	1,877	368	499	**52,539**
0	2,421	4,692	4,598	2,150	610	259	341	6,158	1,050	1,877	375	499	**52,884**
0	2,421	4,692	4,598	2,150	616	259	385	0	1,050	1,877	383	499	**41,354**
0	2,421	4,692	4,598	2,150	622	259	430	0	1,050	1,877	390	499	**41,716**

Table B3 (continued). Hawai'i Estimated Methane Emissions by Landfill (1995-2020), if all parts of any landfill emit methane at a constant rate for 30 years, and new landfills are flared after they begin producing >1,000 tons CH_4/yr.